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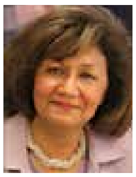

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Conference 9160: Metamaterials, Metadevices, and Metasystems 2014

Sunday - Thursday 17–21 August 2014

Part of Proceedings of SPIE Vol. 9160 Metamaterials: Fundamentals and Applications 2014

9160-1, Session 1

Coherent control in metamaterials for device and system applications *(Keynote Presentation)*

Nikolay I. Zheludev, Univ. of Southampton (United Kingdom) and Nanyang Technological Univ. (Singapore); Kevin F. MacDonald, Eric Plum, Xu Fang, Univ. of Southampton (United Kingdom)

Harnessing the coherent interaction of optical waves on photonic metamaterial nanostructures provides for ultrafast all-optical control, at arbitrarily low intensity, of a wide variety of optical phenomena, from absorption and refraction to optical activity and anisotropy. We introduce this new coherent control concept and explore device and systems application potential in spectroscopy and all-optical data processing through a number of experimental demonstrations.

9160-2, Session 1

Actively tunable metadevices *(Invited Paper)*

Mark L. Brongersma, Geballe Lab. for Advanced Materials (GLAM) (United States)

Many conventional optoelectronic devices consist of thin, stacked films of metals and semiconductors. In this presentation, I will demonstrate how one can improve the performance of such devices by nano-patterning the constituent layers at length scales below the wavelength of light. The resulting metafilms and metasurfaces offer opportunities to dramatically modify the optical transmission, absorption, reflection, and refraction properties of devices. This is accomplished by encoding the optical response of nanoscale resonant building blocks into the effective properties of the films and surfaces. To illustrate these points, I will show how nanopatterned metal and semiconductor layers can be used to enhance the performance of photodetectors, solar cells, and enable new imaging technologies. I will also illustrate how metadevices with actively switchable materials can be used to create active components capable of dynamically manipulating light.

9160-3, Session 1

Natural computing with cognitive photonic networks *(Invited Paper)*

Cesare Soci, Nanyang Technological Univ. (Singapore)

We provide proof-of-principle demonstrations of natural computing using simple fiber networks. Thanks to the fast propagation speed of optical signals and to the inherent parallelism of optical networks, linear networks can efficiently solve polynomial (e.g. the matrix inversion) and nondeterministic polynomial (e.g. the Hamiltonian path) mathematical problems. Moreover, nonlinear Erbium doped or chalcogenide fibers can be used to implement metaheuristic optimization, such as the famous ant colony algorithm, or to realize all-optical neuromorphic systems that effectively mimic axon and synapse functionalities. We argue that this framework may be readily extended to integrated silicon photonics or plasmonic waveguide networks to tackle problems of greater complexity.

9160-4, Session 1

Image quality assessments of metamaterial-based microwave remote sensing systems

Steve T. Kacenjar, Lockheed Martin Corp. (United States); David Thomas Crouse, The City College of New York (United States); Igor Bendoym, Tamelia Ali, Phoebus Optoelectronics, LLC (United States); Paul Okun, Lockheed Martin Corp. (United States)

With the advent of lightweight, low cost and spatially stationary metamaterial-based microwave scanning/imaging systems, key questions remain as to their imaging quality effectiveness relative to current beam directing and shaping methods. Methods such as varactor-controlled metamaterials and metasurfaces provide distinctive approaches in steering and shaping the microwave radiation, yet their robustness to operational bandwidth and off-axis deployment may limit their utility in various operational setting such as in portal remote sensing, radar and communication systems. This paper compares the beam shaping performance of two metamaterial approaches under extended bandwidth and off-axis deployment operations to that of near-diffraction limited operational systems.

The first approach, metamaterial stacks, has a split-ring resonator (SRR) multi-layer geometry with varactor shunts between each two-ring unit cell comprising the metamaterial lattice. These varactors provide local control of the phase profile of the beam along the metasurface. The second approach, metasurfaces, rely on a mode-lock laser to temporarily write “chevon” shaped latent image structures onto a semiconductor surface. These structures are areas of excited charge carriers that make these areas of the semiconductor pseudo-metallic. The shape and location of these structures induce local phase changes of the beam. With both approaches, the phase-profile control can be used for beam focusing and steering.

The High Frequency Structural Simulator (HFSS) will model both approaches to estimate the Modulation Transfer Function (MTF) performance across the operational band for both on-axis and off-axis source configurations. These results are then compared with theoretical diffraction-limited performance and current operational systems.

9160-5, Session 2

Gap plasmon-based metasurfaces: fundamentals and applications *(Invited Paper)*

Michael G Nielsen, Sergey I. Bozhevolnyi, Univ. of Southern Denmark (Denmark)

Plasmonic metasurfaces, i.e., nm-thin surface metal nanostructures with subwavelength-sized lattice units, have recently attracted considerable attention due to their abilities to efficiently control both phase and amplitude of transmitted and reflected radiation. We have recently shown that metal nanostructures, in which the bottom metal layer is covered with a thin dielectric layer while the top layer consists of a periodic array of metal nanobricks, thus supporting gap surface plasmon (GSP) resonances, offer improved control of the phase and amplitude of the reflected light. Astutely choosing the thickness of a dielectric spacer, one can realize various operational regimes: from efficient broad or narrowband light absorption that can be exploited for black gold effect or color printing to efficient reflection with the adjustable phase that can be used for phase-gradient metasurfaces. In this talk, the underlying physical mechanisms involved in the process of light reflection by GSP structures are elucidated. Various designs of GSP resonator arrays are considered that are tailored for specific applications, including realization of independent phase gradients in the reflected light for different polarizations, polarization controlled coupling to propagating surface plasmon-polariton modes and other optical functionalities.

9160-6, Session 2

Nonlocal polarization approach to metasurfaces *(Invited Paper)*

Viktor A. Podolskiy, Christopher M. Roberts, Sandeep Inampudi, Univ. of Massachusetts Lowell (United States)

Over last several years new diffraction-based platforms for manipulating the flow of light emerges as a viable tool for ultra-compact photonics. This platform, known as metasurfaces, is based on arrays of planar optical resonators, fabricated at the interface between two dielectrics, arranged to produce diffracted waves of a pre-designed amplitude and direction. Since the majority of light-matter interactions happen within the near-field proximity of the interface, metasurfaces are an optical analog of two-dimensional graphene.

Optics of metasurfaces are fundamentally different from optics of volumetric composite materials. Although finite-difference and finite-element tools can, in principle, be used to characterize the optics of metasurfaces, these techniques require volumetric meshes of a large structure with subwavelength resolution. Due to their two-dimensional nature, metasurfaces cannot be characterized by an effective permittivity or effective index, rendering conventional effective medium techniques useless to describe optics of diffractive structures. Here we propose an analog of effective medium techniques for metasurfaces by characterizing metasurfaces by two-dimensional polarizability. Since the typical spatial profiles of metasurfaces are inhomogeneous on the wavelength scale, polarizability becomes strongly nonlocal (dependent on the wavevector). Nonlocality is known to enable propagation of multiple waves in volumetric structures. Similarly, nonlocal polarization yields diffraction in two-dimensional metasurfaces. We develop the set of boundary conditions that can be used to quantitatively describe diffraction by metasurfaces and compare the predictions of the developed formalism to full-wave solutions of Maxwell equations. The developed formalism can be used as a new convenient tool for understanding, designing, and optimization of metasurface optics.

9160-7, Session 2

Broadband phase delay and frequency conversion with metasurfaces

Vincent Ginis, Vrije Univ. Brussel (Belgium); Philippe Tassin, Chalmers Univ. of Technology (Sweden); Thomas Koschny, Ames Lab. (United States); Costas M. Soukoulis, Iowa State Univ. (United States) and Foundation for Research and Technology-Hellas (Greece)

Metasurfaces—or sheet metamaterials—have revolutionized the manipulation of optical signals through the interaction with a nanostructured surface whose unit cells consist of subwavelength antenna structures. These metasurfaces can reproduce several three-dimensional optical devices, including lenses, mirrors and wave plates, by imposing phase discontinuities across optically flat surfaces. To date, these phase shifts remain limited between 0 and 2π, intrinsically limiting the operational bandwith of metasurfaces. In this contribution, we demonstrate metasurfaces whose bandwidth of operation can be broadened by way of a specific constellation of coupled Lorentzian resonators and we discuss how the bandwidth depends on the number of implemented resonances. Finally, we extend the scope of these metasurfaces and introduce a mechanism that allows for the frequency conversion of optical signals.

9160-8, Session 2

Performance and stability analysis of nonlocal polarization approach to the optics of metasurfaces

Christopher M. Roberts, Sandeep Inampudi, Viktor A. Podolskiy, Univ. of Massachusetts Lowell (United States)

Metasurfaces, optically thin structure with engineered diffraction, have gained attention in the past few years as new platform for ultra-compact photonics. Due to the quasi-two dimensional nature of metasurfaces results in the majority of light-matter interaction near-field the interfaces of dielectrics and metasurface. Therefore, conventional techniques for calculating light interaction with composite systems (metamaterials), that have been developed with volumetric material in mind, are typically inefficient in understanding the optics of metasurfaces. Moreover, since the optics of metasurfaces are more akin to the two dimensional structure graphene than to the traditional optics of volumetric composites, traditional effective medium theories cannot be used to describe the diffractive optics by characterizing the metasurface as an effective index or an effective permittivity/permeability.

A new technique for calculating diffraction by the metasurfaces has been recently proposed. In contrast to the majority of computational or analytical technique, the proposed formalism does not require introduction of effective index to describe interaction of light with metasurface. Instead, we treat the metasurface as a two-dimensional sheet with finite (nonlocal) polarizability, and relate the amplitudes of transmitted and reflected beams to each other via boundary conditions. We show that adequate treatment of optics of metasurfaces requires discontinuity of both normal and tangential components of electric fields, and present a comprehensive comparison between conventional techniques for solving Maxwell equations and the proposed nonlocal polarization model. This presentation focuses on analysis of convergence, stability, and memory/time performance of the proposed formalism.

9160-9, Session 2

High-transmittance all-dielectric Huygens' metasurfaces

Isabelle Staude, Manuel Decker, The Australian National Univ. (Australia); Matthias Falkner, Friedrich-Schiller-Univ. Jena (Germany); Jason Dominguez, Sandia National Labs. (United States); Dragomir N. Neshev, The Australian National Univ. (Australia); Igal Brener, Sandia National Labs. (United States); Thomas Pertsch, Friedrich-Schiller-Univ. Jena (Germany); Yuri S. Kivshar, The Australian National Univ. (Australia)

Metamaterial Huygens' surfaces - reflectionless surfaces that can be realized by two-dimensional subwavelength arrays of polarizable particles with both electric and magnetic response [1,2] - have been suggested for efficient beam steering [1,2], beam shaping [1], and focusing [2] in the microwave [1] and mid-infrared spectral range [2]. However, existing realizations [1] and proposed designs [2] are based on plasmonic meta-atoms, and cannot be directly transferred to near-infrared or even visible frequencies because of the high dissipative losses of plasmonic structures at optical frequencies.

Here we demonstrate, for the first time, metamaterial Huygens' surfaces for near-infrared frequencies by replacing the plasmonic meta-atoms by high-permittivity all-dielectric nanoparticles with tailored Mie-type resonances [3]. We experimentally measure both amplitude and phase of light transmitted through a fabricated metasurface exhibiting spectrally overlapping electric and magnetic dipole-type modes in the near-infrared spectral range. We observe 360 degrees phase variation of the transmitted light in combination with high transmittance values. Our experimental measurements are in excellent agreement with numerical simulations and analytical coupled-dipole calculations which further indicate that near-unity transmittance can be achieved for an optimized experimental structure. This high transmittance in combination with the simultaneously observed strong phase response that provides complete phase coverage is key for the realization of a wide range of applications including efficient wavefront shaping, dispersion control devices, and holograms.

[1] C. Pfeiffer et al., Phys. Rev. Lett. 110, 197401 (2013).

[2] F. Monticone et al., Phys. Rev. Lett. 110,203903 (2013).

[3] I. Staude et al., ACS Nano 7, 7824 (2013).

9160-10, Session 2

Metasurfaces inner symmetries: from square lattices to quasicrystalline layouts

Sergey S. Kruk, The Australian National Univ. (Australia); Alexander Poddubny, Ioffe Physico-Technical Institute (Russian Federation); Christian Helgert, Friedrich-Schiller-Univ. Jena (Germany); Manuel Decker, Isabelle Staude, The Australian National Univ. (Australia); Christoph Menzel, Christoph Etrich, Carsten Rockstuhl, Friedrich-Schiller-Univ. Jena (Germany); David A. Powell, The Australian National Univ. (Australia); Thomas Pertsch, Friedrich-Schiller-Univ. Jena (Germany); Dragomir N. Neshev, Yuri S. Kivshar, The Australian National Univ. (Australia)

Metamaterials and metasurfaces rely on the ability to design and fabricate nanoparticles of various shapes – meta-atoms - and to place them in a user-defined arrangement. This allows for the creation of composite metamaterials optimized for a desired operation and functionality with respect to their interaction with electromagnetic radiation. The properties of metamaterials are commonly defined by the response of the individual meta-atoms, usually at normal incidence [1]. However, different types of meta-atom arrangements as well as different directions of excitation lead to different coupling conditions among meta-atoms, and as a result, to different optical responses [2]. Here we study and exploit an extra degree of freedom in metamaterial design – symmetry of their inherent arrangement.

Theoretically we use two complimentary approaches. First, we utilized the advanced Jones calculus [3] to describe qualitatively influence of the inherent symmetries on the optical properties. Second, we use coupled dipoles approach, applicable for quantitative analysis of the power of symmetry-dependant metamaterial response. In our experiments, we employ rotationally symmetric metal-dielectric meta-atoms sustaining both electric and magnetic artificial response. The use of symmetric meta-atoms allows detecting the optical effects dependant on the lattice symmetry only, including circular dichroism and optical activity. All the analytical predictions and experimental measurements are in a good agreement and are fully supported by full-wave numerical calculations.

Our findings allow for the first time the quantitative analysis of the impact of inter-element coupling and lattice symmetry on the optical properties of metamaterials, and they constitute an important step towards the design of metasurfaces with desired optical properties.

[1] C. M. Soukoulis and M. Wegener, Nat. Photon. 5, 523 (2011)

[2] M. Decker et al., Phys. Rev. B 84, 085416-7 (2011).

[3] C. Menzel et al., Phys. Rev. A 82, 053811(2010).

9160-11, Session 3

Single-photon source based on NV center in nanodiamond coupled to TiN-based hyperbolic metamaterial *(Invited Paper)*

Vladimir M. Shalaev, Mikhail Y. Shalaginov, Purdue Univ. (United States); V. V. Vorobyov, Photonic Nano-Meta Technologies (Russian Federation); A. V. Akimov, Russian Quantum Ctr. (Russian Federation); Alexei Lagutchev, Purdue Univ. (United States); Vasily V. Klimov, P.N. Lebedev Physical Institute (Russian Federation); Alexander V. Kildishev, Alexandra Boltasseva, Purdue Univ. (United States)

We experimentally demonstrate both the lifetime reduction and the enhancement of single-photon emission from nitrogen-vacancies in nanodiamonds coupled to a hyperbolic metamaterial (HMM) based on TiN/AlScN superlattice. Our results pave the way towards future CMOS-compatible integrated quantum sources. Coupling NV centers to HMM allows for the spontaneous emission efficiency of single-photon emitters to be engineered over a broad spectral range. This enhancement is a result of a drastic increase in the photonic density of states within an HMM, providing numerous extra radiative channels to the emitter. In addition, our superlattice structures make use of CMOS compatible materials, thereby opening new highways for the fabrication of integrated CMOS compatible single-photon sources.

9160-12, Session 3

Nonlinear vortex and solitonic behaviour in hyperbolic metamaterial applications *(Invited Paper)*

Allan D. Boardman, Peter Egan, Univ. of Salford (United Kingdom)

The fascinating world of structured material sustaining structured light, such as spinning light beams, is investigated with the aim of revealing new and exciting pathways to applications in modern digital control of our environment. Vortex generation and propagation properties have a beautiful history, and the possibility of generating them together with magnetooptic control in hyperbolic metamaterials offers some important new horizons and they will be discussed in detail. An emphasis will be placed on the fact that certain members of the soliton family have a lot of application possibilities, especially when placed into the context of materials being used in a light-controlling-light environment. The latter phenomenon is suitable for optical chips of the future. Both spatial and temporal solitons will be invoked with an emphasis upon narrow beams and extremely short pulses. It will be pointed out, very strongly, that detailed control of light-packets can also be introduced especially by the deployment of the anisotropy offered by hyperbolic metamaterials in the optical frequency range. In order to stimulate the main features of this kind of metamaterial activity, an exact study of wave propagation in anisotropic waveguides is required. It is an added advantage to be able to use magnetooptics, which is a, globally, very advanced technology and is now being carefully assessed, globally, to combat any integration difficulties into optical circuitry. All the complex structures that will be examined will include the kind of soliton-like channels available from modern experimental facilities and a special consideration will be given to neighbouring interface interactions. A wide range of metamaterials, will be examined, showing that the outcomes of the investigations presented here will lead to a new range of exotic optical switching.

9160-13, Session 3

Photonic hyper-crystals *(Invited Paper)*

Evgenii Narimanov, Purdue Univ. (United States)

In this talk, I introduce a new “universality class” of artificial optical media - the photonic hyper-crystals. These hyperbolic metamaterials with a periodic spatial variation of dielectric permittivity on a subwavelength scale, combine the features of optical metamaterials and photonics crystals within the same medium, and allow for an unprecedented degree of control of light propagation.

Metamaterials and photonic crystals currently represent the primary building blocks for novel nanophotonic devices. With the goal of ultimate control over the light propagation, an artificial optical material must rely on either the effect of a subwavelength pattern that changes the average electromagnetic response of the medium, or on Bragg scattering of light due to a periodic variation that is comparable to the wavelength. By virtue of this inherent scale separation, the corresponding metamaterial- and photonic crystal paradigms, while complementary, are generally considered mutually exclusive within the same environment.

The situation is however very different in the world of hyperbolic metamaterials, where the opposite signs of the dielectric permittivity components in two orthogonal directions lead to a hyperbolic dispersion of TM-polarized propagating waves, with the wave numbers unlimited by the frequency. As a result, a periodic variation in the dielectric permittivity, regardless of how small is its period, will necessarily cause Bragg scattering of these high-k waves, leading to the formation of photonic bandgaps in both the wavenumber and the frequency domains, with profound consequences on wave propagation and scattering in these photonic hyper-crystals.

9160-14, Session 3

Self-assembled tunable photonic hyper-crystals

Vera N. Smolyaninova, Bradley Yost, David Lahneman, Towson Univ. (United States); Evgenii Narimanov, Purdue Univ. (United States); Igor I. Smolyaninov, Univ. of Maryland, College Park (United States); Thomas Gresock, Towson Univ (United States)

We demonstrate a novel artificial optical material, a “photonic hyper-crystal”, which combines the most interesting features of hyperbolic metamaterials and photonic crystals. Similar to hyperbolic metamaterials, photonic hyper-crystals exhibit broadband divergence in their photonic density of states due to the lack of usual diffraction limit on the photon wave vector. On the other hand, similar to photonic crystals, hyperbolic dispersion law of extraordinary photons is modulated by forbidden gaps near the boundaries of photonic Brillouin zones. Three dimensional self-assembly of photonic hyper-crystals has been achieved by application of external magnetic field to a diluted cobalt nanoparticle-based ferrofluid. Unique spectral properties of photonic hyper-crystals lead to extreme sensitivity of the material to monolayer coatings of cobalt nanoparticles, which should find numerous applications in biological and chemical sensing.

9160-15, Session 4

Hyperbolic metamaterials: Kronig Penney approach *(Invited Paper)*

Jacob B. Khurgin, Johns Hopkins Univ. (United States)

Hyperbolic optical metamaterials is an interesting class of extremely artificial materials that exhibit metallic or dielectric properties depending on the polarization. Effective medium approach predicts that the wavevectors can be infinitely high, although in practicability they are limited by the periodicity of the metamaterials (often referred to as “nonlocality”). In this talk we examine a different approach, based on Kronig Penney modal and show how one can obtain dispersion, group velocity, density of states, and the loss of hyperbolic metamaterial without reverting to extensive numerical calculations. Our approach shows that hyperbolic materials can be interpreted as coupled arrays of gap plasmons, and also reveals an interesting fact, missing form effective medium model) that elliptical and hyperbolic dispersions can coexist in the material at certain frequencies.

9160-16, Session 4

Enhanced spontaneous emission from the inside of a multilayer hyperbolic metamaterial

Lorenzo Ferrari, Dylan Lu, Dominic Lepage, Zhaowei Liu, Univ. of California, San Diego (United States)

Hyperbolic metamaterials (HMMs) allow the engineering of spontaneous emission (SE), with broadband and tunable features. However, in the current configurations the emitters are dispersed on top of the HMM, which does not maximize the radiation-matter coupling.

The present study optimizes the SE enhancement of a point source, modeled as a dipole, by including it inside a multilayered silver (Ag)/silicon (Si) HMM. Two figures of merit quantify the performance of the emitter, with respect to its behavior in a homogeneous environment: the Purcell factor (PF), which describes the decay speed enhancement, and the radiative enhancement (RE), which represents the far-field increase of emitted power. First, we demonstrate the tunability of the PF for an outer point source by varying the percentage of Ag in a single period of the multilayer. Then we move the dipole inside each individual Si layer and compute the respective Purcell enhancements. We observe a significant enlargement in bandwidth, with spectral features dependent on the dipole polarization. The PF inside the structure reaches a value of almost 300, 3 times larger than that achieved outside. To scatter into the far field the radiation trapped in the HMM, we implement a triangular grating with a pitch of 300 nm, and rectangular grating with a pitch of 200 nm and a slit width of 40 nm. The emitter is embedded in a layer of polymethyl methacrylate (PMMA), a host material commonly used in fabrication. A 10-fold and 6-fold RE are obtained in the triangular and rectangular grating respectively.

9160-17, Session 4

Experimental realization of broadband super absorber based on rainbow trapping in hyperbolic metamaterials

Dengxin Ji, Haomin Song, Xie Zeng, Hai-feng Hu, Kai Liu, Nan Zhang, Qiaoqiang Gan, Univ. at Buffalo (United States)

Thin-film perfect absorbers are important optical/thermal components required by a variety of on-chip applications, including photon/thermal-harvesting, thermal energy recycling, and vacuum heat liberation. Recently, researches on metal-insulator-metal (MIM) metamaterials based perfect absorber and trapped “rainbow” storage of light have attracted considerable interests. However, these researches are limited by either narrow absorption band or relatively low coupling efficiency. In this work, we experimentally realize a patterned hyperbolic meta-film with engineered and freely tunable absorption band from near-IR to mid-IR spectral regions based on multilayered metal/dielectric hyperbolic metamaterial (HMM) waveguide taper. By cascading resonant MIM perfect absorber elements with gradually tuned widths along the vertical direction, the absorption band of the patterned HMM film is extended significantly. As the incident light is coupled into the HMM waveguide taper, the group velocity of the waveguide mode at different wavelength can be reduced significantly at their corresponding critical widths, resulting in the enhanced light-matter interaction [1]. In addition, multi-patterned HMM metafilms is also demonstrated to reduce the required number of metal/dielectric layers, and therefore simplifying the sample preparation and experimental realization of on-chip broadband super absorbers. The ability to efficiently produce broadband, highly confined and localized optical fields on a chip is expected to create new regimes of optical/thermal physics, which holds promise for impacting a broad range of energy technologies ranging from photovoltaics, to thin-film thermal absorbers/emitters, to optical-chemical energy harvesting.

Reference

[1] Hu, H., et.al. Rainbow Trapping in Hyperbolic Metamaterial Waveguide. Sci. Rep. 3, 1249 (2013).

9160-18, Session 4

Optical characterization of multilayered hyperbolic metamaterials

Thejaswi U. Tumkur, Yuri A. Barnakov, Mikhail A. Noginov, Norfolk State Univ. (United States); Vladimir Liberman, MIT Lincoln Lab. (United States)

We compare two different methods designed to determine the dielectric permittivity components and the ENZ (Epsilon-Near-Zero) wavelength in lamellar Au and Ag-based metal/dielectric metamaterials with hyperbolic dispersion. The first measurement method utilizes polarized angular reflectance measurements. The second measurement technique relies on generalized ellipsometry in an anisotropic measurement mode. The experimental data obtained with the two techniques are in reasonable agreement with the permittivity values calculated using effective medium predictions for a two-component uniaxial medium. It is shown that the extracted permittivity values are sensitive to imperfections in fabrication and chemical oxidative degradation due to ambient storage effects.

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9160-19, Session 4

Design of hyperbolic metamaterials by genetic algorithm

Ian A. Goforth, Hossein Alisafaee, Daniel B. Fullager, Christopher Rosenbury, Michael A. Fiddy, The Univ. of North Carolina at Charlotte (United States)

Based on the unique optical characteristics and applications of Hyperbolic Metamaterials (HMM), we consider a design method to find the optimal performance of such structures. We employ a powerful optimization approach, called genetic algorithm (GA), to “naturally” find HMM structures that are globally optimized for specific applications. To do this, we investigate the effectiveness of a few fitness functions incorporated within the GA and evaluate their results based on the degree of convergence and computation times and also the tolerances of the final structures. Moreover, we discuss and compare the possible fabrication challenges in realizing the HMMs based on these designs. Further, we try to optimize the performance of conventional HMMs using GA to obtain improvements in the spectral features of these structures. We then compare the results of these three cases: 1) conventional design, 2) GA-assistedconventional design, and 3) full-GA optimization. Finally, we make conclusions about the advantages and disadvantages of using GA for optimization purposes in HMMs.

9160-20, Session 4

Non-elastic light scattering in hyperbolic medium *(Invited Paper)*

Alexander Poddubny, Ioffe Physico-Technical Institute (Russian Federation) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Ivan V. Iorsh, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Pavel Ginzburg, Anatoly V. Zayats, King’s College London (United Kingdom); Pavel A. Belov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Yuri S. Kivshar, The Australian National Univ. (Australia)

We present a theoretical study of the non-elastic light scattering in the hyperbolic medium. Hyperbolic medium is a uniaxial medium where the two main components of the dielectric tensor have opposite signs. This leads to the hyperbolic surface of wave vectors corresponding to the given frequency, which, in turn, enhances the density of photonic states. Such effect is known to strongly modify the light-matter interaction with the most notable example being the Purcell effect. However, most of the current studies are limited to the coherent optical processes.

Here, we investigate non-elastic scattering of the light in the hyperbolic medium when photon energy is transferred to the quasiparticles, such as electrons (Compton scattering) or phonons (Brillouin or Raman scattering). We demonstrate, that the scattering selection rules are drastically changed in the hyperbolic regime due to the modified photon dispersion. We also perform a rigorous quantum mechanical analysis of the scattering problem using the Huttner-Barnett local quantization scheme, which allows us to account for the losses. Our study indicates, that the Compton scattering cross section in the visible spectral range and the Compton shift are strongly enhanced as compared to that in vacuum and this effect can be observed experimentally.

9160-500, Session Plen

Non-Covalent Interactions of Carbon Nanotubes in Polymer Composites

Eva M. Campo, Bangor Univ. (United Kingdom)

Despite much effort to control dispersion, alignment, and overall processing of Carbon Nanotubes, both their surface chemistry and distribution in polymer matrices remain an active topic of research. Growth and processing can yield local defects along the graphitic structure to become effective latching sites conducive to polymeric interaction; a prelude to dispersion. With all, the possibility of controlled surface chemistry paves the way of CNTs towards supramolecular chemistry. In this scheme, π-π and CH-π interactions play an important role in time-evolved bonding dynamics; which in turn, is exhorted by both chemistry and processing. We will engage in an exploration that provides insights into bonding in nanocomposites, offering invaluable information towards the synthesis-structure-property paradigm.

9160-501, Session Plen

Nanoscale Silicon as an Optical Material

Philippe M. Fauchet, Vanderbilt Univ. (United States)

As the material at the core of all microelectronic devices, silicon has fueled most technological revolutions in the 20th century. It is abundant and, among inorganic materials, inexpensive. Due to extremely large industrial investments over the past decades, it was tamed like no other material before. However, with the possible exception of the photovoltaic industry, silicon has until recently been used by a single industry. The situation started changing over 20 years ago when advances in the manufacture of nanometer-size objects (e.g., quantum dots, wires, sheets) and devices with deep submicron features (e.g., photonic crystals) allowed researchers to manipulate the properties of bulk silicon and to exploit the unusual optical properties of nanoscale silicon structures. In this presentation, the history, including the most recent developments, of nanoscale silicon as an optical material will be reviewed with a special emphasis on active and biosensing structures.

9160-502, Session Plen

Nanoscale Engineering Optical Nonlinearities and Nanolasers

Shaya Fainman, Univ. of California, San Diego (United States)

Dense photonic integration requires miniaturization of materials, devices and subsystems, including passive components (e.g., engineered composite metamaterials, filters, etc.) and active components (e.g., lasers, modulators, detectors). This paper discusses passive and active devices that recently have been demonstrated in our laboratory, including monolithically integrated short pulse compressor utilized with silicon on insulator material platform and design, fabrication and testing of nanolasers constructed using metal-dielectric-semiconductor resonators confined in all three dimensions.

9160-22, Session 5

Graphene enabled nanoantenna based opto-electro-mechanical biosensor *(Invited Paper)*

Ertugrul Cubukcu, Univ. of Pennsylvania (United States)

Graphene as a monolayer of carbon atoms in a honeycomb lattice has attracted significant interest for its unique optical, electrical, mechanical properties for a range of applications. Metal based plasmonic devices and sensors can capitalize on graphene for unprecedented new functionalities if synergistically integrated. One such intriguing property of graphene that plasmonics can benefit from is its impermeability to gas molecules even as small as a single He atom. Capitalizing on this we demonstrated that nanoantennas made of silver, the ideal plasmonic material that tends to oxidize due to sulfur containing ambient gases, can be effectively passivated with a monolayer graphene. Due to its atomic thickness, graphene also does not perturb nanoantenna near-fields significantly maintaining the full potential of silver nanoantennas in sensing applications.

Graphene is also a very promising material as a bioactive layer due to its ability to effectively adsorb biomolecules through pi-pi stacking interactions. If graphene is used as a monolayer functionalization layer, lengthy sensor surface modification steps will not be necessary. We studied the binding affinities between several different proteins and graphene and found that adsorption can be as strong as that of a specifically binding antigen-antibody pair.

We will also discuss a new multimodal opto-electro-mechanical device that synergistically combines a graphene field effect transistor based nanoelectronic sensor and a nanoantenna based photonic sensor on a mechanical resonator sensor. This hybrid approach combining electrochemical, refractive index, and mass sensing functions on the same device footprint opens up new directions in nano-bio-sensors with unprecedented features. This proof-of-concept nanosensor experimentally achieves sub-picomolar label-free detection limits across all three independent sensing modes, and possesses a dynamic range that is 2-3 orders of magnitude larger than that of any single mode nanosensor.

9160-23, Session 5

Graphene in electromagnetic metamaterials *(Invited Paper)*

Philippe Tassin, Chalmers Univ. of Technology (Sweden); Nian-Hai Shen, Ames Lab. (United States) and Iowa State Univ. (United States); Maria Kafesaki, Foundation for Research and Technology-Hellas (Greece); Thomas Koschny, Iowa State Univ. (United States); Costas M. Soukoulis, Iowa State Univ. (United States) and Foundation for Research and Technology-Hellas (Greece) and Ames Lab. (United States)

Graphene is a two-dimensional material system consisting of carbon atoms arranged in a honeycomb lattice. It is just one atom thick and exhibits many unusual mechanical, electrical and optical properties. In this contribution, we present the results of our studies on how graphene can be useful to create metamaterials in the terahertz, infrared, and visible ranges of the electromagnetic spectrum. Graphene is potentially useful for use in metamaterials, because (1) it allows for miniaturization down to the atomic length scale; (2) its tunable Fermi level allows for unprecedented tunability of electromagnetic structures made of this material; (3) it has a highly reactive response, resulting in strongly localized, deeply subwavelength plasmons and deep subwavelength resonators; and (4) it may provide broadband gain. At optical frequencies, the conductivity of graphene is too small to obtain useful metamaterial response from patterned graphene sheets, but it can provide tunability when combined with metallic metamaterials [Opt. Express 20, 12198 (2012)]. In the near-infrared, graphene offers highly confined surface plasmons, which are plagued by considerable dissipative loss, though [Nature Photon. 6, 259 (2012)]. At terahertz frequencies, we compare a series of experimental measurements for the dynamic terahertz conductivity of graphene with recently proposed terahertz graphene metamaterial structures metamaterials made from patterned graphene [Science 341, 620 (2013)]. In addition, we compare split-ring resonators made from graphene versus gold and discuss the properties of the electric and magnetic dipole resonances of such split-ring resonators, as well as applications in tunable metamaterials.

9160-24, Session 5

Infrared nano-imaging and nano-spectroscopy of graphene plasmons

Zhe Fei, Univ. of California, San Diego (United States); Aleksandr S. Rodin, Boston Univ. (United States); Wenzhong Bao, Univ. of Maryland, College Park (United States); Zeng Zhao, Univ. of California, Riverside (United States); Martin Wagner, Siyuan Dai, Mengkun Liu, Alexander S. McLeod, Univ. of California, San Diego (United States); Gerardo Dominguez, California State Univ., San Marcos (United States); Alex Zettl, Univ. of California, Berkeley (United States); Antonio H. Castro Neto, National Univ. of Singapore (Singapore); Mark Thiemens, Univ. of California, San Diego (United States); Fritz Keilmann, Ludwig Maximilian Univ. of Munich (Germany); Chun Ning Lau, Univ. of California, Riverside (United States); Michael M. Fogler, Dimitri N. Basov, Univ. of California, San Diego (United States)

Graphene was predicted to be a candidate material for plasmonics and metamaterials since years ago. But this remains a prediction other than an established fact only until recently, when our groundbreaking experimental works were reported. In this talk, we present first nano-imaging and nano-spectroscopy studies of graphene plasmons using scattering-type scanning near-field microscope –a unique technique allowing efficient excitation and high-resolution imaging of graphene plasmons. With this technique, we were able to show that common graphene/SiO2/Si back-gated structure support propagating surface plasmons in the infrared frequencies. The observed plasmons are highly confined surface modes with a wavelength around 200nm that are conveniently tunable by the back gate voltages [Nature 487, 82–85 (2012)]. In addition, we performed nano-spectroscopy of graphene over a broad range of mid-infrared frequencies, which provides evidence of strong coupling between graphene plasmons and SiO2 optical phonons [Nano Lett. 11(11), 4701-4705 (2011)]. Finally, we were able to map and characterize various types of line defects inside CVD graphene film by exploring real space patterns of propagating surface plasmons. These line defects, including cracks, wrinkles, and even grain boundaries, trigger distinct plasmonic features due to plasmon interference [Nature Nanotech. 8, 821–825 (2013)]. Further modeling and analysis unveiled unique electronic properties associated with these line defects.

9160-25, Session 6

Functional optical metamaterials employing spatial dispersion and absorption *(Invited Paper)*

Andriy Shevchenko, Patrick Grahn, Matti Kaivola, Aalto Univ. School of Science and Technology (Finland)

Non-trivial metamaterials are often composed of anisotropic and asymmetric metamolecules of a size that is only a few times smaller than the wavelength of visible light. This results in a significant spatial dispersion making the wave characteristics dependent not only on the polarization, but also on the propagation direction. Due to spatial dispersion, the material can, for example, show “optical magnetism” even if the magnetic dipole moments of the constituent metamolecules are equal to zero. In addition to spatial dispersion, most functional optical metamaterials exhibit considerable absorption, such that only thin metamaterial films can be considered as transparent. The wave characteristics, such as refractive index (n) and impedance (Z) or electric permittivity and magnetic permeability, in such a material will depend on the orientation of the material's entrance facet, which determines the wave attenuation direction.

We present a relatively simple semianalytical method to theoretically treat and design spatially dispersive and absorptive optical metamaterials. The approach enables one to calculate the parameters n and Z for any polarization and incidence angle of light analytically in terms of the reflection and transmission coefficients of a single layer of metamolecules. We also discuss ways in which the spatial dispersion and absorption can be used to control optical beams. As an example, a metamaterial slab can be designed to provide divergence-free propagation of an optical beam independently of the beam's transverse profile and angle of incidence or to reflect light differently by the different facets of the slab.

9160-26, Session 6

Light filaments based free space metamaterial components *(Invited Paper)*

Natalia M. Litchinitser, Zhaxylyk A. Kudyshev, Scott Will, Univ. at Buffalo (United States); Martin C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

The development of ordered structures of filaments opens the possibility of creating conductive filament structures capable of guiding microwaves or terahertz frequency radiation. In this talk we discuss a fundamentally new approach for manipulating microwaves in air based on unique physical properties of hyperbolic metamaterials formed of plasma filaments in air. We show that filament-based hyperbolic metamaterials can be used for focusing, guiding and steering radar signals to facilitate new degrees of freedom in the detection of such signals in realistic environments. Further, we theoretically and numerically demonstrate that by variation of realistically available parameters of virtual hyperbolic metamaterials, such as fill-fraction of plasma filaments and recombination rate of free electrons with positive ions inside the filament channels, it is possible to design various metamaterial components in the free space for increasing the angular and range resolution of microwave radar systems, and show that they can survive in adverse environments.

9160-27, Session 6

Plasmonic and metamaterial devices based on opto-mechanical interactions

Pavel Ginzburg, Alexey V. Krasavin, King's College London (United Kingdom); Alexander S. Shalin, Pavel A. Belov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Yuri S. Kivshar, The Australian National Univ. (Australia); Anatoly V. Zayats, King's College London (United Kingdom)

Optical forces are of significant interest from both fundamental and applicative points of view. Typical optical forces achievable with reasonable light intensities are, in nano-to-pico Newton range. One of the approaches for optical forces enhancement relies on the increase of the fields plasmonic nanostructures. In this talk we will demonstrate several novel effects, related to classical and quantum opto-mecanical effects inspired by plasmonic nano-structures and metamaterial assembly [1, 2].

One of the intriguing effects, that will be presented, emerges from novel quantum-mechanical self-induced torques acting on an emitter situated in structured material environment. We further demonstrated, that dipole situated within hyperbolically anisotropic metamaterial applies giant self-induced torque and deterministically aligns itself in the prescribed direction. The magnitude of the torque is order of magnitudes larger than in any other anisotropic materials existing in nature.

Other interesting opto-mechanical phenomenon that will be discussed in this contribution relies on sub-diffractional confinement of guided plasmonic modes and the ability to enhance and engineer forces on nano-scale. Here we propose and demonstrate the concept of force-induced nonlinear optical interactions. In general light beams of different frequencies cannot interact directly, however they could if a mediating material object is present. Nonlinear materials are commonly used for this purpose. Here we propose a new approach to control light with light, based on a nano-opto-mechanical system integrated in a plasmonic waveguide is proposed. Opto-mechanical motion of a free-floating resonant nanoparticle in a subwavelength plasmonic V-groove waveguide is used in the prototype.

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9160-28, Session 6

Tailoring dispersion by strong coupling

Thejaswi U. Tumkur, Guohua Zhu, Devon Courtwright, Mikhail A. Noginov, Norfolk State Univ. (United States)

We study the strong coupling of dye molecules to surface plasmons polaritons of thin silver films. The dispersion splits into three branches and demonstrates avoided crossing, characteristic of strong coupling. The dispersion is further modified, when gain is introduced, by strongly pumping the dye molecules. In a series of complementary experiments, we also show that dye molecules can be strongly coupled to localized plasmons modes of rough silver films and also multilayered hyperbolic metamaterials. Our preliminary results could pave the way for a new class of hybrid plasmonic materials and metamaterials.

9160-29, Session 6

Extraordinary optical transmission in the scope of nonlocality

Johan Christensen, Christin David, N. Asger Mortensen, DTU Fotonik (Denmark)

Plasmons in metals can oscillate on a sub-wavelength length scale and this large-k response constitutes an inherent prerequisite for fascinating effects such as perfect imaging, ENZ super squeezing, etc., just to name a few. Nonlocal response has previously been found to pose limitations to field-enhancement phenomena. Accounting for nonlocal hydrodynamic response in thin perforated metal film, we present a detailed study into the properties and influences of the extraordinary optical transmission.

9160-30, Session 6

On the electrodynamics of moving permanent dipoles in external electromagnetic fields

Masud Mansuripur, College of Optical Sciences, The Univ. of Arizona (United States)

Whereas Maxwell's macroscopic equations relate the electric and magnetic fields to their material sources (i.e., charge, current, polarization and magnetization), Poynting's theorem governs the flow of electromagnetic energy and its exchange between fields and material media, while the Lorentz law regulates the back-and-forth transfer of momentum between the media and the fields. The close association of momentum with energy thus demands that the Poynting theorem and the Lorentz law remain consistent with each other, while, at the same time, ensuring compliance with the conservation laws of energy, linear momentum, and angular momentum. This paper shows how a consistent application of the aforementioned laws of electrodynamics to moving permanent dipoles (both electric and magnetic) brings into play the rest-mass of the dipoles. The rest mass must vary in response to

external electromagnetic fields if the overall energy of the system is to be conserved. The physical basis for the inferred variations of the rest-mass appears to be an interference between the internal fields of the dipoles and the externally applied fields. We use two different formulations of the classical theory in which energy and momentum relate differently to the fields, yet we find identical behavior for the rest-mass in both formulations.

9160-31, Session 7

Plasmonic vibrational sensing in the mid-infrared *(Invited Paper)*

Frank Neubrech, Harald Giessen, Univ. Stuttgart (Germany)

Infrared spectroscopy is ideally suited for a label-free and direct characterization of molecular species. Inconveniently, the analysis of small amounts of molecules, which is of large interest for sensing applications, is hampered by their relative low extinction cross-sections. One possibility to overcome this limitation is to use surface-enhanced infrared spectroscopy (SEIRS), where large electromagnetic near-fields provided by plasmonic excitations of metal nanoparticles are employed to enhance signals from molecular vibrations. Such strongly enhanced fields are of great interest for sensing applications, e.g., the detection of molecules by their vibrational fingerprints in the infrared with applications in analytical science, medicine, explosive detection, etc. However, this principle of nanoantenna-assisted SEIRS has been proved for example to detect self-assembled monolayers of molecules with attomolar sensitivity but can also applied to detect more complex molecules, like organic molecules, biologically relevant peptides or proteins.

As a first demonstration of infrared vibrational sensing of biomolecules we covered nanoantennas with a specially designed collagen peptides. To do so, a flow cell was used giving us the unique possibility to control the collagen adsorption on the nanostructures and to perform in-situ SEIRS in aqueous solutions. For antennas with different lengths the plasmonic resonance fairly coincides with the amide I and amide II bands of the collagen peptide. Depending on the ratio of the vibrational and plasmonic excitation we observe differently enhanced vibrational signal with Fano-type line shapes. In comparison to conventional infrared spectroscopy such vibrational signals are enhanced by up to four orders of magnitude.

9160-32, Session 7

Experimental verification of heat flux bending in multilayered thermal metamaterials

Krishna K. Vemuri, Prabhakar Bandaru, Univ. of California, San Diego (United States)

We demonstrate heat flux bending in a multilayered composite considering an effective medium approximation. We show that when the orientation of the composite is physically rotated with respect to the applied temperature gradient , the resultant thermal conductivity tensor can be modified to be anisotropic, with non-zero off- diagonal elements. The resultant anisotropy was found to be dependent on the angle of rotation as well as of the ratio of the thermal conductivities of the constituent materials.

We experimentally demonstrate the bending of the heat flux in three such multilayered composites made by alternately stacking 2mm thick layers of copper ~ 391 W/mK and alloy steel ~ 42 W/mK respectively with three different rotation angles. Temperature profiles in the composites were imaged using an infrared camera (FLIR A320) and agreed closely with the simulations [1]. We show that the resultant heat flux vectors in the composites are oriented at an angle with the applied temperature gradient , due to anisotropy in the thermal conductivity.

Our experiments and analysis indicate that heat flux does not have to be collinear with the applied temperature gradient, e.g. the temperature gradient in a particular direction can drive heat flux in an orthogonal direction. Our studies have implications in thermal energy management with possible utility in portable electronics, nano-combustible systems, solar energy utilization etc.

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9160-33, Session 7

Infrared absorption by coupled surface plasmon modes in an ultra-thin metamaterial

Peter A. Hobson, QinetiQ Ltd. (United Kingdom); Piers Andrew, Nokia Research Ctr. (United Kingdom); Benny T. Hallam, Imerys Minerals Ltd. (United Kingdom); Chris R. Lawrence, QinetiQ Ltd. (United Kingdom)

We report infrared reflectivity measurements from an ultra-thin metamaterial system supporting a textured top mirror spaced above a perfect electrical conductor by a subwavelength dielectric spacer. The surface texturing causes the structure to diffractively couple to free radiation. Furthermore, the structure supports flat-band, surface plasmon absorption modes at discrete intervals across the infrared spectrum.

The nature of the band structure is different depending on whether the incident field is transverse electric (TE) or transverse magnetic (TM) polarized. The TE data shows three distinct modes, each of which maintain coupling over all angles of incidence. The TM data shows a more complex band structure; with modes positioned at the wavenumbers corresponding to TE modes and additional modes spaced at frequencies midway in-between. The fundamental TM mode mirrors the TE mode and maintains coupling for all angles of incidence, but higher order TM modes exhibit an angle-dependent coupling. We also observe a sub-fundamental TM mode that is due to phonon absorption within the dielectric spacer layer of the structure.

The nature of the electromagnetic modes, their mutual interactions and the device band structure haves been characterized by finite element and other numerical modelling of the experimental data. With the exception of the phonon mode, the analyzed modes show that absorption of incident radiation predominantly occurs in the metal layers of the structure, at frequencies dictated by the geometry of the patterned top surface and shown to be a series of odd and even standing wave solutions.

9160-34, Session 7

Thermal radiation control: enhancement of solar cell performance and daytime radiative cooling *(Invited Paper)*

Shanhui Fan, Sunil Sandhu, Stanford Univ. (United States); Zongfu Yu, Univ. of Wisconsin-Madison (United States); Aaswath P. Raman, Linxiao Zhu, Marc Anoma, Stanford Univ. (United States)

Nanophotonic and meta-material structures provide new opportunities for the control of thermal radiation. Here we show that such control of thermal radiation can be used to enhance the open circuit voltage of solar cells, and to achieve passive daytime radiative cooling.

9160-35, Session 7

Vanadium dioxide: a tunable disordered metamaterial and applications *(Invited Paper)*

Federico Capasso, Mikhail A. Kats, Shriram Ramanathan, Harvard School of Engineering and Applied Sciences (United States)

In VO_2 thin films, the Insulator-to-Metal transition occurs gradually with increasing temperature: Nanoscale inclusions of the metallic phase emerge in the surrounding insulating-phase VO2, which grow and connect in a percolation process, eventually leading to a fully metallic state at the end of the transition.The unique temperature-dependent dispersion of this effective medium was used to demonstrate that a film of VO2 , with thickness (~150 nm) much smaller than the wavelength, deposited on sapphire can operate as a temperature tunable absorber; in particular, nearly perfect absorption was achieved at a particular temperature for a narrow range of infrared wavelengths. The reflectivity of such a device varies dramatically and non-monotonically across the phase transition, with the strong absorption feature appearing during an intermediate state of VO2 as a result of coupling to an ``ultra-thin-film resonance. Since the emissivity of an object is equal to its frequency-dependent absorptivity (Kirchoff's law) such a thin-film VO2 -sapphire structure is expected to have an emissivity that also depends strongly and non-monotonically on temperature. This structure displays ``perfect" blackbody-like thermal emissivity over a narrow wavelength range (approximately 40 cm-1, surpassing the emissivity of our black-soot reference. We observed large broadband negative differential thermal emittance over a > 10 C range: Upon heating, the VO -sapphire structure emits less thermal radiation and appears colder on an infrared camera.

9160-36, Session 7

Thermal instability in plasmonics

Andrey K. Sarychev, Institute for Theoretical and Applied Electrodynamics (Russian Federation); Alexei L. Bogdanov, Western Digital Corp. (United States); Gennady Tartakovsky, Advanced Systems & Technologies, Inc. (United States); Sergey Vergeles, L.D. Landau Institute for Theoretical Physics (Russian Federation); Vladimir Parfenyev, Ilya A. Fedorov, Moscow Institute of Physics and Technology (Russian Federation)

Plasmon nanolasers, also known as SPASERs, attract much attention in recent years due to the numerous potential applications in the plasmonics. We consider thermal effects in the metal nanoresonator immersed in the active medium. The size of the resonator is much less than the wavelength. The plasmon field inside the nanoresonator operates as a quantum object. Due to the nanosize of the resonator the internal plasmon electric field is on the order of the atomic field even for few plasmon quants. The coupling between the plasmon field and plasmon resonator is anomalous strong. We develop the quantum dynamics of the plasmon field and show that the SPASER may be the subject of thermal instability. When number of the plasmon is maintained at the stationary level the loss increases with increasing the temperature of the SPASER. Therefore, the heat generation increases with the increasing the temperature. We have positive feedback and corresponding thermal instability. When the energy, accumulated in the plasmon nanoresonator, exceeds the instability threshold the temperature increases exponentially. We find the increment of the temperature growth and lifetime as function of the loss in metal and the structure of the plasmon resonator. We consider how the thermal instability influence the luminescence and find how the lasing threshold is changed. The coherence of the light emitted by the plasmon laser is also considered. The thermal stability of the nanolaser is important for many

9160-37, Session 8

Manipulating phase and power flow with electromagnetic metamaterials *(Invited Paper)*

Anthony Grbic, Gurkan Gok, Univ. of Michigan (United States)

Transformation electromagnetics (EM) has provided an entirely new approach to designing electromagnetic devices. In transformation EM, a targeted field distribution is derived from an initial one through a coordinate transformation. The form invariance of Maxwell's equations under coordinate transformations is then exploited to calculate the transformed material parameters needed to support the targeted field distribution. However, finding the coordinate transformation that yields a desired electromagnetic field distribution is not always straightforward and may not be possible.

Here, an alternative electromagnetic design approach is introduced. Material parameters are defined in terms of desired distributions of phase progression and power flow direction. First, spatial distributions of the wave vector and direction of Poynting vector are stipulated within the medium. From these two distributions, the required anisotropic and inhomogeneous material parameters needed to support such propagation are found. The material parameters are then implemented using metamaterials. Such spatial control of phase and power flow allows the phase and amplitude of a field profile to be arbitrarily tailored. The proposed synthesis method will find use in the design of antennas and beamforming networks, as well as in scattering control. In addition, the methodology could provide a novel approach to signal routing, the design of mode conversion devices, and the generation of extreme radiating apertures and exotic beams.

9160-38, Session 8

Guiding, switching, and sensing with nanorod metamaterials *(Invited Paper)*

Gregory A. Wurtz, Wayne Dickson, Pavel Ginzburg, Alexey V. Krasavin, Anatoly V. Zayats, King's College London (United Kingdom)

Invited talk: Controlling photonic processes on length scales below the diffraction limit requires structural elements with dimensions much smaller than the wavelength. Recently, novel plasmonic metamaterial has been developed based on arrays of aligned plasmonic nanorods which can be designed to exhibit hyperbolic dispersion or epsilon-near-zero behaviour. This metamaterial provides a flexible platform with tuneable optical properties across the visible and telecom spectral range. Such metamaterials can be used instead of conventional plasmonic metals for designing plasmonic waveguides, plasmonic crystals, label-free bio- and chemo-sensors, for development nonlinear plasmonic structures with the enhanced nonlinearities, and controlling emitters. In this talk, we will overview fundamentals and applications of plasmonic nanorod metamaterial for designing new types of nanostructured plasmonic platforms, bio- and chemical sensing components, and nonlinear optical devices.

9160-39, Session 8

Voltage tunable mid-infrared metamaterials based on strong light-matter coupling

Alexander Benz, Ines Montano, John F. Klem, Igal Brener, Sandia National Labs. (United States)

Metamaterials provide excellent characteristics for optical filters covering the entire range from visible to radio frequencies. Their optical reflectance and transmittance depend primarily on the geometry of the individual sub-wavelength resonators and not on bulk material properties. However, realizing an actively tunable metamaterial that can be used as an optical filter or modulator remains challenging.

Here we present the design and experimental realization of an electrically tunable metamaterial at mid-infrared wavelengths. Our devices operate in the strong light-matter coupling regime where energy is periodically exchanged between the metamaterial (the optical cavity) and intersubband transitions (the two-level system). We can tune the intersubband energy continuously from 28.5 THz (at zero bias) to 34.1 THz (at 5 V) by applying a bias across the quantum-well stack. Due to the strong coupling between two-level system and metamaterial cavity, we also tune the spectral device response. We can shift the upper polariton frequency continuously over 2.5 THz (corresponding to 8% of the center frequency or one full linewidth) by changing the external bias from zero to 5 V.

This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Portions of this work were supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

9160-40, Session 8

Mechanical tuning of metasurface made from stand-up split ring resonators

Fan Zhou, Chen Wang, Biqin Dong, Xiangfan Chen, Cheng Sun, Northwestern Univ. (United States)

Recently, many efforts have been made toward creating metasurfaces based on the static local tuning of electrical response of material to the light. However, very limited study has been conducted for the response to the magnetic component of incoming light, which shows substantial effect in metasurfaces by generating a non-unity or even negative permeability that does not exist in nature, especially extending the metasurfaces with mechanical tunability to modulate optical properties in the visible or near-infrared range. In this project, we firstly demonstrate the tunable metasurface subject to the external dynamic excitation. A novel route is developed to fabricate the metasurface composed of vertically aligned split ring resonator (SRR) array with U-shaped cross-section using nanotransfer printing process. Such a metasurface allows for full coupling of the magnetic field component at all angles of incidence, leading to much higher excitation efficiency with respect to the excitation of the planar SRR array. As the U-shaped SRR faces upwards rather than in plane, two beams of the SRR are free standing and thus can be driven by the force induced by the electromagnetic resonance. When the circulating current in the coil is excited by a pulse TM polarized light, strong magnetic field at resonant frequency concentrates inside the SRR gap and induces forces to actuate the beams to their mechanical resonance modes. Using a narrow-band laser source, the measured resonance shift caused by the change of the gap distance matches with simulation result.

9160-21, Session 9

Extreme plasmonics in atomically thin materials *(Keynote Presentation)*

Javier García de Abajo, ICFO - Institut de Ciències Fotòniques (Spain); Alejandro Manjavacas, Rice Univ. (United States)

Plasmons in graphene feature several advantages with respect to more conventional materials, including a large electro-optical tunability and extreme optical-field enhancement, which are suitable building blocks to produce complete optical absorption, extreme light modulation, and ultra sensitive response down to the single-molecule level. Other atomically thin materials also exhibit similar properties. We will discuss here the challenges and opportunities introduced by these types of materials, including their application to quantum optics, electro-optical devices, and sensing.

9160-42, Session 9

Localized surface phonon polariton resonances in cuboidal silicon carbide nanopillar arrays

Chase T. Ellis, Joseph G. Tischler, Orest J. Glembocki, U.S. Naval Research Lab. (United States); Francisco J. Bezares, U.S. Naval Research Lab. (United States) and American Society for Engineering Education (United States); Richard Kasica, National Institute of Standards and Technology (United States); Loretta Shirey, Joshua D. Caldwell, U.S. Naval Research Lab. (United States)

Polar dielectrics, such as silicon carbide, are capable of supporting plasmonic-like effects through the excitation of phonon-mediated collective charge oscillations (Surface phonon polaritons, SPhP). The absence of free carriers in these materials provides a low-loss alternative to metal-based plasmonic materials that exhibit high optical losses. In this study, we investigate the optical response of localized SPhP resonances in fixed-height (950nm), fixed-length (400nm) 4H-SiC, cuboidal nanopillars that vary in width (400nm-6,400nm), and thus aspect ratio. We find that these low-loss nanostructures yield high Q-factor, polarization-dependent, localized SPhP resonances that can be tuned over a wide spectral range. FTIR reflectance measurements using incident light polarized parallel or perpendicular to the width of the cuboidal nanostructure were performed to measure the various localized SPhP resonances. Overall, more than 4 distinct localized SPhP resonances are excited by each polarization, including a monopole resonance that is excited by both polarizations. By changing the nanopillar aspect ratio (AR=width/length), we demonstrate that these localized SPhP resonances can be tuned over a broad spectral range. All resonances exhibit narrow linewidths (3cm^-1 to 30 cm^-1) that correspond to high quality factors in the 30-300 range. The elongated cuboid geometry is of particular interest, since each polarization can stimulate SPhP resonances that span different spectral ranges; thus, yielding a spectral response that is tunable via polarization control.

9160-43, Session 9

Non-steady-state organic plasmonics and its application to optical control of Coulomb blocking in nanojunctions

Guangqi Li, Northwestern Univ. (United States); Boris D. Fainberg, Holon Institute of Technology (Israel) and Tel Aviv Univ. (Israel)

Purely organic materials characterized by low losses with negative, near-zero, and smaller than unity dielectric permittivities can be easily fabricated [1]. Here we develop a theory of non-steady-state organic plasmonics with strong short laser pulses [2] that enable us to obtain near-zero dielectric permittivity during a short time only. Our consideration is based on the model of the interaction of strong (phase modulated) laser pulse with organic molecules, Ref.[3], extended to the dipole-dipole intermolecular interactions in the condensed matter [4].

We have proposed to use non-steady-state organic plasmonics for the enhancement of intersite dipolar energy-transfer interaction in the quantum dot wire that influences on electron transport through nanojunctions [5]. Such interactions can compensate Coulomb repulsions for particular relationships between their values [6]. We propose the exciton control of Coulomb blocking in the quantum dot wire based on the non-steady-state near-zero dielectric permittivity of the organic host medium using chirped laser pulses.

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9160-45, Session 9

Superdirective dielectric resonator antenna

Alexandr E. Krasnok, Dmitry S. Filonov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Constantin R. Simovski, Aalto Univ. School of Electrical Engineering (Finland); Yuri S. Kivshar, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation) and The Australian National Univ. (Australia); Pavel A. Belov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

We propose and demonstrate experimentally a simple approach for achieving superdirectivity of emitted radiation for electrically small antennas based on a spherical dielectric resonator with a notch. Superdirectivity is achieved without using complex antenna arrays and for a wide range of frequencies. We also demonstrate the steering effect for a subwavelength displacement of the source. In contrast to conventional superdirective antennas, our design has significantly smaller losses, radiation efficiency up to 80 %, and matching in 3% frequency band.

9160-46, Session 10

Is there a metamaterial route to high temperature superconductivity? *(Invited Paper)*

Igor I. Smolyaninov, BAE Systems (United States); Vera N. Smolyaninova, Towson Univ. (United States)

Superconducting properties of a material, such as electron-electron interactions and the critical temperature of superconducting transition can be expressed via the effective dielectric response function of the material. Such a description is valid on the spatial scales below the superconducting coherence length (the size of the Cooper pair), which equals ~100 nm in a typical BCS superconductor. Searching for natural materials exhibiting larger electron-electron interactions constitutes a traditional approach to high temperature superconductivity research. Here we point out that recently developed field of electromagnetic metamaterials deals with somewhat related task of dielectric response engineering on sub-100 nm scale. We argue that the metamaterial approach to dielectric response engineering may considerably increase the critical temperature of a composite superconductor-dielectric metamaterial.

9160-47, Session 10

Visualizing catalytic reactions and light-matter interactions in plasmonic materials and metamaterials with sub-nanometer-scale resolution *(Invited Paper)*

Jennifer A. Dionne, Stanford Univ. (United States)

We present new electron-beam spectroscopic techniques that enable visualization of nanoparticle phase transitions in reactive environments and light-matter interactions in three dimensions. We focus particular attention on plasmonic materials and metamaterials that could form the basis for future meta-devices and meta-systems. First, we directly monitor hydrogen absorption/desorption in individual palladium nanocrystals with sizes ranging from tens of nanometers down to just a few nm. Our approach is based on in-situ electron energy-loss spectroscopy (EELS) in an environmental transmission electron microscope. By probing hydrogen-induced shifts of the palladium plasmon resonance, we find that hydrogen loading and unloading isotherms are characterized by abrupt phase transitions and macroscopic hysteresis gaps. These results suggest that alpha and beta phases do not coexist in single-crystalline nanoparticles, in striking contrast with conventional first-order phase transitions and ensemble measurements of Pd nanoparticles. Then, we then extend these techniques to monitor nanoparticle reactions in a liquid environment. By constructing a flow chamber, we directly monitor growth and assembly of colloidal plasmonic metamaterial constituents induced by chemical catalysts. Lastly, we introduce a novel tomographic technique, cathodoluminescence spectroscopic tomography, to probe optical properties in three dimensions with nanometer-scale spatial and spectral resolution. Particular attention is given to reconstructing a 3D metamaterial resonator supporting broadband electric and magnetic resonances at optical frequencies. Our tomograms allow us to locate regions of efficient cathodoluminescence across visible and near-infrared wavelengths, with contributions from material luminescence and radiative decay of electromagnetic eigenmodes. The experimental signal can further be correlated with the radiative local density of optical states in particular regions of the reconstruction. Our results provide a general framework for visualizing chemical reactions and light-matter interactions in plasmonic materials and metamaterials, with sub-nanometer-scale resolution, and in three-dimensions.

9160-48, Session 10

Settling the controversy of Forster energy transfer (FRET)

Cristian L. Cortes, Zubin Jacob, Univ. of Alberta (Canada)

Control of energy transfer in nanophotonic environments is important for applications in organic photovoltaics, OLEDs, as well as molecular imaging and sensing devices. Specifically, short-range intermolecular energy transfer such as Forster resonance energy transfer (FRET) occurs when molecules are less than 10nm apart. Engineering the spontaneous emission lifetime of molecules is achieved through control of the local density of states (LDOS) ?(r,?). It has been assumed that the LDOS can also govern processes like the FRET rate between molecules [1-2]. From this premise, recent experimental work has concluded that the FRET rate is unaffected by the nanophotonic environment. Here, we show that the non-local spectral density function See(r,r',?) should be used as the correct physical quantity governing intermolecular energy transfer rates. We also show that the FRET rate can be engineered in specific nanophotonic environments.

Generally the density of states is defined through the dyadic Greens function at a point i.e. G(rD, rD,?) . From its definition, it is clear that the LDOS is a local quantity that only depends on the location of the donor molecule rD. To describe a non-local process like intermolecular energy transfer, we define the non-local spectral density See(rA, rD, ?)= |nA·G(rA, rD,?)·nD, based on semi-classical theory [3] or quantum theory of energy transfer [4]. Note that it depends on the location of the donor molecule as well as the location of the acceptor molecule within the inhomogeneous environment. To confirm that this quantity correctly describes the physical process of energy transfer, we have reproduced the experimental results from [1]. We define this as the non-local dipole spectral density which is a physical quantity equivalent to the Purcell factor used to characterize spontaneous emission From our simulations, we found excellent agreement between the predictions using SEE and their observed results. Briefly, [1] studied the effect of the environment by placing different donor-acceptor pairs a specific distance away from a silver mirror. The observed constant FRET rate was a result of the relatively large separation distance ranging from 60-200nm away from the mirror, as compared to the intermolecular separation distance of 7nm. We found that if the donor-acceptor pairs were placed closer to the mirror (1-20nm) then there would be a noticeable change in the energy transfer rate. Of course, this prediction would only be valid so long as the local medium and weak-coupling approximation remain valid as well.

To conclude, we have proposed using the non-local spectral density function See to describe FRET rates within inhomogeneous environments. We have found that this quantity demonstrates that it is possible to engineer FRET in nanophotonic environments, despite recent experimental work. This work should impact future experimental studies as well as engineering applications like FRET-based imaging, sensing, and solar harvesting.

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9160-49, Session 10

Effect of rotation symmetry on the optical activity using planar meta-nanostructures

Eng Huat Khoo, Yew Li Hor, A*STAR Institute of High Performance Computing (Singapore); Eunice Leong, Yanjun LIu, IMRE (Singapore)

In this paper, we design layered composite meta-structures to investigate its' effect on the optical activity and circular dichroism (CD). The layered composite meta-structures consist of thin gammadion nanostructure with thickness lamda/10, where lamda is the incident wavelength. The layered meta-structures are alternate between a dielectric and gold (AU) material. Each layered composite meta-gammadion is arranged together in an array of pitch 700 nm. In the first case, 3 layers of meta-gammadion, with metal-insulator-metal (MIM) and insulator-metal-insulator (IMI) configuration are simulated with material properties from optical hand book. There are 3 modes in the CD spectrum, which can be characterized into Bloch CD mode and hybrid CD modes. Compared with the CD spectrum of whole structure of gammadion in gold with same total height, the CD of the MIM layered composite are larger. When the number layer increase to 5, it is observed that the CD is reduced by 30% and there is a red shift in the Bloch CD mode and a slight blue shift in the hybrid CD modes. By further increasing the number of layers to 7, we observed further CD increment and larger wavelength shift in the CD modes. The layered composite meta-gammadion is fabricated using template stripping method. Experimental results also show excellent agreement with the simulation results for CD and wavelength shift. We submerge the layered meta-gammadion into a solution of chiral molecules. The CD spectrum of the meta-gammadion shows a larger wavelength shift compared to pure metal structures. This indicate a more sensitive and robust detection of chiral molecules.

9160-51, Session 10

Demonstration of the magnetic Purcell effect in wire metamaterials

Alexey P. Slobozhanuk, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Alexander Poddubny, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation) and Ioffe Physical-Technical Institute (Russian Federation); Alexandr E. Krasnok, Pavel A. Belov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

In our contribution, we present experimental study of the magnetic Purcell effect in the finite array of wires in the microwave frequency range and reveal the full spatial-frequency map of the Purcell factor. We investigate Purcell effect in the stationary regime of source feeding where Purcell factor determines a change of time average power emitted by a subwavelength source. In our case, source represents a subwavelength loop probe.

To provide experimental investigation, we designed a wire metamaterial resonator as an 14?14 array of brass wires. Wire length, radius and lattice period are equal to 20 cm, 0.1 cm and 1 cm, respectively. The probe presented a small loop with the diameter 1.2 cm, connected by the coaxial cable to the vector network analyzer. The loop probe was fixed in the precise coordinate scanner, oriented parallel to the metamaterial surface. The scanner moved along the wires at the height h = 0.2 cm above the metamaterial. This allowed us to measure the Purcell factor in dependence on the coordinate along wires.

The Purcell factor has peaks at the frequencies, corresponding to the subwavelength-volume Fabry-Perot modes of the wire medium resonator. The Purcell factor enhancement is most brightly manifested for the low order modes. Thus, tailoring of the subwavelength-volume Fabry-Perot modes, which are very different from those of the conventional dielectric resonators, allows one to obtain the independent control over the density of states and the spatial distribution of the electromagnetic field.

9160-41, Session 11

Linear and nonlinear properties of all-dielectric metamaterials *(Invited Paper)*

Dragomir N. Neshev, Isabelle Staude, The Australian National Univ. (Australia); Maxim Shcherbakov, Lomonosov Moscow State Univ. (Russian Federation); Andrey E. Miroshnichenko, Manuel Decker, The Australian National Univ. (Australia); Andrey A. Fedyanin, Lomonosov Moscow State Univ. (Russian Federation); Igal Brener, Sandia National Labs. (United States); Yuri S. Kivshar, The Australian National Univ. (Australia)

For more than a decade, optical metamaterials have relied on plasmonic nanoparticles to achieve a number of unique properties, such as artificial magnetism. However plasmonic structures inherently suffer from strong dissipative losses at optical frequencies, which are critically hampering their performance. A new route to overcome this key problem has been opened by the experimental observations of electric and magnetic Mie-type resonances in high-permittivity all-dielectric nanoparticles [1]. Such nanoparticles exhibit very low losses at optical frequencies and for non-spherical particles the magnetic and electric resonances can be individually engineered to tailor both magnetic and electric polarizabilities. When combined together, such high-permittivity nanoparticles can form a new class of lossless metamaterials and metasurfaces, thus opening novel applications in nanophotonics, including wavefront engineering or advanced light sources.

This talk will overview our activities on all-dielectric metasurfaces based on silicon nanodisks [2], which allow for individual tuning of their electric and magnetic resonances. The possibility to engineer the resonances enables us to achieve unique linear and nonlinear optical properties of the metasurfaces. In particular, we show the suppression of backward scattering in the case of spectral mode overlap [2], as well as the efficient spectral shaping of emission of quantum dots in close proximity to the metasurface. Finally we study experimentally third harmonic generation in our structures and investigate the possibility to enhance the nonlinear optical response by realising nano-clusters of silicon disks.

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9160-52, Session 11

Developing ceramic materials for practical plasmonics *(Invited Paper)*

Alexandra Boltasseva, Nathaniel Kinsey, Urcan Guler, Jongbum Kim, Purdue Univ. (United States); Gururaj V. Naik, Stanford Univ. (United States); Vladimir M. Shalaev, Purdue Univ. (United States)

The field of plasmonics has long been dominated by noble metals, which lack both tunability of their optical properties and CMOS-compatibility. Alternative plasmonic materials, such as transition metal nitrides and transparent conducting oxides (TCOs), offer a solution to these problems and enable consumer plasmonic devices across many fields including

localized surface plasmon resonance (LSPR), integrated optical circuitry, and metamaterials. Among the transition metal nitrides, titanium nitride (TiN) has shown promise as a plasmonic material in the visible and near infrared (NIR). For LSPR applications, TiN nanoparticles exhibit resonances that overlap with the biological transparency window, thus enabling nanoscale medical applications. In addition, TiN has a similar optical efficiency to gold, is chemically stable, thermally stable, and is bio-compatible. TiN has also recently been demonstrated as a successful material for integrated plasmonic applications, with waveguiding structures achieving surface plasmon polariton (SPP) propagation lengths exceeding 5 mm. Such structures can easily be integrated with plasmonic modulators, which use the tunability of TCOs to attenuate a SPP wave. Electro-optic plasmonic modulators have achieved an extinction ratio of 46 dB/um, with a coupling loss of 1 dB. In this talk, various plasmonic ceramic materials will be discussed for plasmonic devices with enhanced flexibility and performance across many avenues of nanophotonic research.

9160-53, Session 11

Manufacturing of bulk nanoplasmonic materials and metamaterials by micro-pulling down method *(Invited Paper)*

Dorota A. Pawlak, Katarzyna Sadecka, Marcin Gajc, Karolina Korzeb, Pawel Osewski, Andrzej Klos, Barbara Surma, Institute of Electronic Materials Technology (Poland); Alessandro Belardini, Grigore Leahu, Concita Sibilia, Univ. degli Studi di Roma La Sapienza (Italy)

Two novel bottom-up manufacturing methods of nanoplasmonic materials and metamaterials will be presented utilizing the crystal growth techniques: (i) directional solidification of eutectic composites [1], and (ii) direct doping of dielectric matrices with plasmonic nanoparticles (NanoParticles Direct Doping - NPDD) [2]. Eutectics are simultaneously monolithic and multiphase materials forming self-organized micro/nanostructures, which enable: (i) the use of various component materials including oxides, semiconductors, metals, (ii) the generation of a gallery of geometrical motifs and (iii) control of the size of the structuring, often from the micro- to nanoregimes. On the other hand, the novel method of direct doping of dielectric matrices with nanoparticles utilizing directional solidification provides three-dimensional nanoplasmonic materials enabling doping with nanoparticles of various chemical composition, various size and shape, as well as co-doping with other chemical agents. Materials with plasmonic resonances at visible and IR wavelengths, as well as materials with enhanced photoluminescence and up-conversion as well as with anomalous refraction [3] will be presented. Our new approach may lead to novel manufacturing solutions for photonic applications in areas photonics, optoelectronics, photovoltaics.

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9160-54, Session 11

Principles of vortex light generation from nanoscale arrays *(Invited Paper)*

David L. Andrews, Mathew D Williams, David S Bradshaw, Univ. of East Anglia (United Kingdom); Ruifeng Lui, David B Phillips, Sonja Franke-Arnold, Miles J Padgett, University of Glasgow (United Kingdom)

Light beams with unusual forms of wavefront offer a host of useful features to extend the repertoire of those developing new optical techniques. Complex, non-uniform wavefront structures offer a wide range of optomechanical applications, from microparticle rotation, traction and sorting, through to contactless microfluidic motors. Beams combining transverse nodal structures with orbital angular momentum, or vector beams with novel polarization profiles, also present new opportunities for imaging and the optical transmission of information, including quantum entanglement effects. Whilst there are numerous well-proven methods for generating light with complex wave-forms, most current methods work on the basis of modifying a conventional Hermite-Gaussian beam, by passage through suitably tailored optical elements. Based on symmetry arguments, the direct generation of complex beams by spontaneous emission was until recently considered impossible. However, newly emerging principles indicate that nanofabricated emitter arrays, cast in an appropriately specified geometry, can overcome the obstacles. This presentation introduces the methods and reports on the latest advances, which are potentially paving the way for new laser sources.

9160-55, Session 11

Tunable linear and nonlinear optical properties of transparent conductive oxides for Si-compatible active nanoplasmonics

Antonio Capretti, Boston Univ. (United States) and CNR-SPIN (Italy); Yu Wang, Boston Univ. (United States); Nader Engheta, Univ. of Pennsylvania (United States); Luca Dal Negro, Boston Univ. (United States)

Transparent Conductive Oxides (TCOs) are emerging as a promising platform for silicon-compatible plasmonic nanostructures and active metamaterials for a variety of different device applications ranging from compact nano-sensors and light sources to energy harvesting components. The electric permittivity of TCOs is negative in the near-infrared spectral range enabling the excitation of plasmonic resonances with sub-wavelength localized electric field and dramatically reduced dissipative losses compared to traditional metal-based plasmonic and metamaterials systems.

In the present work we demonstrate controlled fabrication of Aluminum Zinc Oxide (AZO) and Indium Tin Oxide (ITO) thin films with tunable plasmonic response across the 1-2um spectral range, deposited using magnetron sputtering. In addition, we demonstrate light-emitting rare-earth doped TCOs with negative permittivity for novel light-emitting plasmonic devices based on Si-processing. The fabricated samples are investigated using spectroscopic ellipsometry, photoluminescence, scattering spectroscopy, and nonlinear second harmonic generation spectroscopy. Our numerical and experimental results demonstrate tunability of the epsilon-near-zero condition for the fabricated materials and an increased electric field concentration leading to significantly enhanced second-harmonic generation.

In conclusion, our work paves the way to the engineering of tunable active metamaterials based on the widespread Si technology for applications to linear and nonlinear optical devices.

9160-56, Session 11

Experimental demonstration of negative refractive index in principally homogeneous materials (magnetic semiconductors) *(Invited Paper)*

Adil-Gerai Kussow, Alkim Akyurtlu, Yassine Ait El Aoud, Hamzeh M. Jaradat, Univ. of Massachusetts Lowell (United States)

Homogeneous negative refractive index materials are introduced as an alternative to normally utilized inhomogeneous metamaterials. The theory of such materials was developed several years ago (A. Kussow and A. Akyurtlu, PRB 78, 205202 (2008)), and the effect is due to the coexistence of the spin-wave mode with the plasmonic mode, and both modes are activated by the electromagnetic field with simultaneous negative permittivity and permeability responses within the narrow frequency band close to the ferromagnetic resonance. To justify this theory, the thin films of ferromagnetic semiconductor, Cr-doped indium oxide, were fabricated, with clearly measured ferromagnetism at high saturation magnetization and a Curie temperature which is much higher than room temperature. The refractive index, within mid-IR, was extracted from combined transmittance and reflectance data and was compared with theoretical prediction. Also, a direct standard beam displacement method validates the effect of negative refraction in this material.

9160-57, Session 12

Field effect frequency tunable metamaterials *(Invited Paper)*

Harry A. Atwater Jr., Victor W. Brar, Georgia T. Papadakis, Ho Wai Lee, Michelle Sherrott, California Institute of Technology (United States)

The carrier density and optical properties of dielectric and plasmonic materials are typically fixed at the time of fabrication. However field effect tuning of the electrochemical potential in semimetallic materials such as graphene and conducting oxide nanoresonators enables the plasmon and phonon dispersion to be measured. We demonstrate the design of a tunable ENZ metamaterial based on metal and transparent conductive oxide (TCO) multilayers, using the field effect to tune the permittivity of the TCO across thin gate dielectric layers. Gated field effect modulation of the carrier density in graphene nanoresonators in a'perfect absorber' geometry allows for strong modulation of the absorbance. Electrochemical and carrier density modulation in metals yields tunable resonances in metal nanostructures and reveals the plasmoelectric effect, a newly-discovered photoelectrochemical potential. By tuning the permittivity and index to near-zero values, expands the length scale over which coherent quantum emitter phenomena (e.g., concurrence, superradiance) can be observed in epsilon-near-zero media.

9160-58, Session 12

Materials and fields at the nanoscale: design and engineering of active photonic-plasmonic nanostructures *(Invited Paper)*

Luca Dal Negro, Boston Univ. (United States)

The ability to tailor light-matter interactions in metal-dielectric nanostructures is at the heart of nano-optics technology. The exquisite control of propagating and non-propagating electromagnetic fields made possible by the engineering of optical nanomaterials enables innovative approaches for nanoscale electromagnetic field enhancement, concentration and manipulation. In particular, the manipulation of the photonic-plasmonic regime in Fano-coupled active nanomaterials has recently led to broadband linear and nonlinear optical nano-antennas, nanoscale energy concentrators, biosensors, as well as novel types of resonant nano-cavity structures of interest to sub-wavelength light sources and photodetectors with dramatically enhanced emission/absorption optical cross sections.

In this talk, I will present our results on the design, nanofabrication and optical characterization of active nanostructures and metamaterials for on-chip device applications to light sources and nonlinear nano-optics based on the widespread silicon platform. In particular, I will discuss nonlinear and polarization switchable optical nanoantennas as well as our work towards the engineering of low-loss dielectrics with tunable negative permittivity in the near-infrared spectral range. Rare-earth doped conductive oxide nanostructures and active epsilon-near-zero (ENZ) materials are fabricated and their tunable polaritonic responses across the 1-2?m spectral range demonstrated using scattering, photoluminescence and second harmonic generation spectroscopy. Finally, our work on broadband Purcell enhancement of radiation rates in rare earth coupled hyperbolic media will be discussed.

9160-60, Session 12

Bilayer four-fold rotationally symmetric subwavelength nanostructures for chirality switching

Yew Li Hor, A*STAR Institute of High Performance Computing (Singapore)

Chirality effect has been reported from the interaction of light with chiral plasmonic nanostructures. Such nanostructure enhances the chirality response of the chiral molecules and provides a good platform for biochemical sensing and molecular structure manipulation. The ability to detect chiral molecules has been a long term goal of biologists and chemist because chirality is inherent in macromolecules such as proteins and DNA in human body. One of the challenging problems is manipulation of the CD spectrum. Here, we investigate the switchable chiral effects of subwavelength nanostructures array with each of the unit cell. It consists of two layers of gold nanostructures sandwiching a thin layer of SiN with thickness of 50 nm in four-fold rotationally symmetric arrangement. Different nanostructures such as nanorods and nanostripe are investigated. The switchable chirality effect is observed in both plasmonic and Bloch modes when the mutual angle between the first layer and second layer rotates with respect to each other. The magnitude of chirality changes from positive to negative when the mutual angle rotates from 0° to 90°. In the order hand, the nanostructures change from right-handed to left-handed structures without altering the polarization of incident light, or vice versa, upon the mutual rotation angles. Thus, by manipulating the mutual rotation angle, the handedness of the nanostructure will switch and cause the reversal of the outgoing light.

9160-61, Session 13

Guiding waves around the corners: topologically protected photonic transport *(Invited Paper)*

Gennady B. Shvets, Tzuhsuan Ma, S. Hossein Mousavi, The Univ. of Texas at Austin (United States); Alexander B. Khanikaev, Queens College (United States)

We propose a novel and easily realizable platform for making photonic topological insulators. The platform is based on a simple "bed of nails" photonic structure. Our numerical simulations and analytic theory demonstrate the existence of topologically protected surface waves that are conceptually different from the standard surface Tamm states. We will discuss the significance of such topological protection and the possibility of guiding surface waves along sharp zigzag-like trajectories.

9160-62, Session 13

Anisotropic metamaterials to enhance ring imaging Cherenkov detection

Vincent Ginis, Vrije Univ. Brussel (Belgium); Philippe Tassin, Chalmers Univ. of Technology (Sweden); Thomas Koschny, Iowa State Univ. (United States); Costas M. Soukoulis, Iowa State Univ. (United States) and Foundation for Research and Technology-Hellas (Greece)

Cherenkov radiation is a peculiar form of electromagnetic radiation emitted by charged particles that propagate at a velocity larger than the phase velocity of light. In addition to several applications, including the development of novel light sources and the detection of labeled biomolecules, this type of radiation is widely utilized in so-called Ring Imaging Cherenkov (RICH) detectors in high-energy physics experiments. Indeed, at fixed momentum, the Cherenkov cone, which is a measure of the particle's velocity, can be used for the determination of the mass and the identification of the unknown particle. Unfortunately, there exists a trade-off in RICH detectors between the intensity of the generated Cherenkov beam and the accuracy of the velocity measurement. Using the tools of transformation optics, we derive a covariant description of Cherenkov radiation and demonstrate how the Cherenkov intensity and the velocity resolution can be decoupled in a metamaterial radiator. We show that the detector sensitivity is determined by the permittivity of the medium in the perpendicular direction, whereas the intensity of the Cherenkov beam depends on the permittivity in the longitudinal direction. Finally, we show how realistic anisotropic metamaterials, composed of thin metallic cylinders embedded in a dielectric matrix, can enhance the intensity of the generated Cherenkov beam more than a factor two in comparison with state-of-the-art detectors.

9160-63, Session 13

Fluctuational forces in metamaterials

Cristian L. Cortes, Zubin Jacob, Univ. of Alberta (Canada)

In this work we present the first unified approach to understanding Casimir, Casimir-Polder and Van Der Waals interactions in hyperbolic metamaterials. It is seen that inspite of the absorption, dispersion and finite unit cell size significant modifications in the force are exhibited that can be experimentally isolated. We consider a practical thin film structure and use a macroscopic theory of fluctuations to analyze the arising forces.

Our theoretical approach uses Rytov's theory of fluctuational electrodynamics which later led to Lifshitz theory of Casimir Forces. We show how the approach also can be used for Casimir-Polder and Van-Der-Waals interactions and adapted to hyperbolic media. We also show the equivalence of our results to macroscopic quantum electrodynamic approaches.

We take into account experimental non-idealities such as absorption, dispersion and finite unit cell size to obtain the magnitude of the forces in experimental scenarios. This work paves the wave for engineering vacuum and thermal fluctuational forces with metamaterials.

9160-64, Session 13

Singular evanescent wave resonances *(Invited Paper)*

Yu Guo, Zubin Jacob, Univ. of Alberta (Canada)

No abstract available

9160-65, Session 13

Optical spin Hall effect in two-dimensional phase gradient complementary metasurface

Jeong-Weon Wu, Yeon Ui Lee, Ewha Womans Univ. (Korea, Republic of)

Two-dimensional phase gradient metasuface is designed where V-shape antennas are arrayed in a square lattice. In a phase gradient metasurface, the presence of a gradient in refractive index allows for an optical spin Hall effect even for a normally incident light. Spatial separation of two orthogonal circularly polarized lights in the direction vertical to the gradient direction is already reported in the literature. In a two-dimensional phase gradient surface, the gradient direction is determined by the vector sum of each phase gradient, which leads to a spatial separation of two orthogonal circularly polarized lights in the direction newly defined. Focused ion beam is adopted to fabricate a complementary metasurface. First the extraordinary refraction satisfying the generalized Snell's law is examined by experiment, and an FDTD simulation is carried out to compare the experimental results with the theory. Second optical spin Hall effect is examined by a polarization-selective measurement.

9160-66, Session 13

Optical phenomena in multi-periodic plasmonic multilayers

Alexey A. Orlov, Anastasia K. Krylova, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Sergei V. Zhukovsky, Viktoriia E. Babicheva, Technical Univ. of Denmark (Denmark); Pavel A. Belov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Optical properties of plasmonical multilayers of a special type are thoroughly studied. We call a nanostructured multilayer plasmonic when it is comprised of alternating metal and dielectric layers allowing surface plasmon-polaritons (SPPs) to be excited at the metal-dielectric interfaces. It is conventional to consider only two layers that forms the unit cell of the multilayer. In this study we double the number of layers in the unit cell and choose different constitutive materials thus introducing bi-periodicity in our structures. We analyze in details how bi-periodicity transmutes optical properties of plasmonic multilayers and demonstrate phenomena of anomalous tri-refringence, wideband all-angle negative refraction, and nontrivial Dirac-like points.

9160-67, Session 14

Direct laser writing: principles, materials, and applications *(Invited Paper)*

Alexandros Selimis, George Kenanakis, Angelos Xomalis, Maria Kafesaki, Maria Farsari, Foundation for Research and Technology-Hellas (Greece)

We summarize the principles of Direct Laser Writing Microfabrication, and present our recent work in materials processing and functionalization of 3D structures. We also discuss the future applications and prospects for the technology.

9160-68, Session 14

Design, fabrication, and characterization of plasmonic and dielectric metamaterials *(Invited Paper)*

Uriel Levy, Meir Grajower, Boris Desiatov, Liron Stern, Avner Yanai, The Hebrew Univ. of Jerusalem (Israel)

In this talk we present the design, fabrication and experimental characterization of plasmonic and dielectric metamaterials. In particular, we compare metal and dielectric metasurfaces, and show that the latter may be the preferable choice for applications involving transmission optics. Furthermore, we demonstrate significant heating of metallic and metallo-dielectric structures by probing the structures with scanning thermal microscopy in the near field. Finally, we present a new approach for achieving super lensing based on longitudinal modes in the vicinity of the plasma frequency.

9160-69, Session 14

High-throughput nanofabrication of planar chiral metamaterials fabricated using nanospherical-lens lithography *(Invited Paper)*

Yun-Chorng Chang, Academia Sinica (Taiwan) and National Cheng Kung Univ. (Taiwan); Chang-Han Wang, Yu-Min Huang, Fu-Tian Tseng, National Cheng Kung Univ. (Taiwan)

Nanospherical-Lens Lithography (NLL) is an economic fabrication technique that is capable of fabricating nanodisk arrays that cover large area. It utilizes polystyrene nanospheres as focusing lenses to focus the incoming ultraviolet light and exposure the underlying photoresist layer. Photoresist hole arrays form after developing. Metal nanodisk arrays can be fabricated following metal evaporation and lifting-off process. Nanodisk arrays with diameter less than 100 nm and cover an area as large as 1 cm2 are being fabricated regularly using NLL in our research group.

In this study, NLL is used to fabricate nano-ellipse arrays by replacing the light source with a commercial ultraviolet lamp. The UV light from the lamp is propagating differently between the directions perpendicular and parallel to the lamp and therefore demonstrates different focusing behavior. We can control the orientation of the nano-ellipse since the long-axis is found to be parallel to the lamp direction. The Localized Surface Plasmon Resonance (LSPR) of the nano-ellipse arrays is in infrared region when the long-axis length exceeds 1000 nm, which can be used as platforms for surface-enhanced infrared absorption (SERIA). We can also vary the exposure duration, the angle between exposures, and the sample location to fabricate more complicated metamaterials after multiple exposure conditions. In addition, we also demonstrated the fabrication of much smaller patterns, whose LSPR is in the near-infrared. We believe this proposed method is a powerful tool to fabricate multiple metamaterials in large-scale, which will be very useful for various metamaterial applications.

9160-70, Session 14

Layer-by-layer assembled colloidal silver nanoparticle films for SERS applications

Hung-Ying Chen, Meng-Hsien Lin, Shangjr Gwo, National Tsing Hua Univ. (Taiwan)

Surface enhanced Raman spectroscopy (SERS) has received much attention due to its great potential for ultrasensitive detection. However, quantitative SERS measurements are still restricted by the poor uniformity of available SERS substrates. Here, we demonstrate that colloidal Ag nanoparticle films can be utilized as uniform SERS substrates. The close-packed Ag nanoparticles in theses films allow the formation of regular dense arrays of “hot-spots”, which can dramatically enhance the Raman signal in “hot-areas”. We find that this bottom-up method for fabricating tunable SERS substrates is quite simple, robust, and scalable. Therefore, it can become an attractive approach for quantitative SERS applications.

Recently, we have reported that layer-by-layer assembled colloidal noble-metal (Au and Ag) nanoparticle films exhibit strong and tunable plasmonic responses. Here, we experimentally demonstrate that tunable plasmonic metamaterials formed by using colloidal Ag nanoparticle films have the potential to be used as uniform SERS substrates. In this work, the analytes, such as self-assembled monolayers with designated functional groups, are placed on “hot-areas”, which are composed of dense “hot-spots” between close-packed colloidal nanoparticles with tunable coupling strength controlled by nanoparticle surface ligands. We find that the Raman signals from the analytes can be greatly enhanced. Moreover, the spatial mapping of SERS signal is performed to demonstrate the uniformity of SERS signal. It is shown that quantitatively SERS measurement of analyte concentration is feasible.

9160-71, Session 14

Temperature dependent surface modification of silica spheres with methacrylate

Kwang-Sun Kang, Kyungil Univ. (Korea, Republic of)

Temperature dependent surface modification of silica spheres with 3-(Trimethoxysilyl)propylmethacrylate (TMSPM) has been performed. Although the surface of the silica spheres is tried to modify at room temperature, no evidence of the surface modification is observed. The reaction temperatures were varied from 60 to 80°C with various reaction periods. Small absorption shoulder of the C=O stretching vibration showed at approximately 1700 cm-1 for the spheres reacted at 60°C. The clear absorption peak representing the C=O stretching vibration of the ester appeared at 1698 cm-1 for the spheres reacted for 80 min and shifted toward 1720 cm-1 with the increase the reaction time for the spheres modified the surface at 70°C. Strong absorption peak at 1698 cm-1 showed for the spheres modified the surface at 80 °C after 180 min and the absorption peak shifted to 1725 cm-1. The FESEM image shows clear evidence of the modified spheres.

9160-88, Session PWed

Realization of negative index in second-order dispersive metamaterials using standard dispersion models for electromagnetic parameters

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Electromagnetic velocities offer a convenient route to predicting optical refraction in a material as a function of frequency and specific material parameters. Thus, it is known that in domains where the (real parts of) permittivity and permeability of the medium are positive, the resulting phase index is also positive. Conversely, if both these parameters have negative real parts, the material begins to exhibit negative index characteristics. Negative index may be shown to occur when the group and phase velocities in the material become counter-propagating. To examine whether and when this might happen, a spectral approach involving slowly time-varying phasors and chiral constitutive relations was recently developed, and the velocities for dispersive permittivity, permeability and chirality were derived up to first and second order. For both cases, it is found that the presence of chirality automatically makes a propagating plane wave devolve into circular polarizations. Additionally, it is found that the energy velocity is not generally expressible independent of field amplitude for second-order dispersion, unless specific assumptions are made regarding dispersive coefficients for the three parameters of interest. However, phase and group velocities may still be expressed in terms of coefficients only (independent of field amplitude) even for second-order. In this paper, we incorporate in the derived equations physical models (including Debye, Lorentz and Condon) for material dispersion in permittivity, permeability and chirality in order to further examine the consequences of second-order dispersion leading to negative index for practical cases, and also evaluate the resulting phase and group indices.

9160-89, Session PWed

Acoustic metamaterial with negative parameter

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This paper presents modeling, analysis techniques and experiment of metamaterial panel for invisible using. For a unit cell of an infinite metamaterial panel, governing equations are derived using the extended Hamilton principle. The concepts of negative effective mass and stiffness and how the spring-mass-damper subsystems create a stopband are explained in detail. Numerical simulations reveal that the actual working mechanism of the proposed metamaterial panel is based on the concept of conventional mechanical vibration absorbers. It uses the incoming elastic wave in the panel to resonate the integrated membrane-mass-damper absorbers to vibrate in their optical mode at frequencies close to but above their local resonance frequencies to create shear forces and bending moments to straighten the panel and stop the wave propagation. Moreover, a two-dimension acoustic metamaterial panel consisting of lumped mass and elastic membrane is proposed in the lab. We do experiments on the model and The results validate the concept and show that, for two-dimension acoustic metamaterial panel do exist two vibration modes. For the wave absorption, the mass of each cell should be considered in the design. With appropriate design calculations, the proposed two-dimension acoustic metamaterial panel can be used for absorption of low-frequency waves and hence expensive micro-manufacturing techniques are not needed for design and manufacturing of such metamaterial panel for low-frequency waves absorption/isolation .

9160-90, Session PWed

Anderson localization for discretely disordered metamaterials: effect of polarization and off-axis incidence

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We consider polarization and off-axis incidence effects for one-dimensional photonic bandgap structures consisting of alternating layers of positive and negative index materials (PIM/NIM), with one or more parameters discretely disordered. Such long randomly disordered systems exhibit Anderson localization, whose effects can be studied using the Lyapunov exponent of the product of independent identically distributed random transfer matrices modeling the structure. We use Furstenberg's integral formula to calculate Lyapunov exponents for s and p polarizations, and for a range of angles of incidence for these random matrix models. Furstenberg's integral formula requires integration with respect to the probability distribution of the randomized layer parameters, and integration with respect to the so-called invariant probability measure of the direction of the vector propagated by the long chain of random matrices. This invariant measure can rarely be calculated analytically, so some numerical technique must be used to produce the invariant measure for a given random matrix product model. Here we use the method of Froyland-Aihara, especially suited for discretely disordered parameters, to calculate the invariant measure. This method produces the invariant measure from the left eigenvector of a certain sparse row-stochastic matrix. This sparse matrix represents the probabilities that a vector in one of a number of discrete directions will be transferred to another discrete direction via the random transfer matrix. The Froyland-Aihara method results in a dramatic reduction in computation time to calculate Lyapunov exponents compared to traditional layer or vector iteration methods.

9160-91, Session PWed

Design of periodic plasmonic photocoupler for infrared optoelectronics

Zhenghua An, Fudan Univ. (China)

Similar to the antenna in microwave regime, plasmonic resonances of periodic metal structures are favorable for coupling electromagnetic energy or photons efficiently into optoelectronic devices and therefore boost their performance, thanks to the surface electromagnetic waves or surface plasmon polariton. In this work, we demonstrate that a plasmonic cavity consisting of a periodically perforated metal film and a flat metal sheet separated by a semiconductor spacer is particularly suitable for multicolor infrared light detection, due to the excellent spectral tunability, spatially distinct field distributions and absorption enchancement. Three different types of optical modes are clearly identified --- the propagating and localized surface plasmons on the perforated metal film and the Fabry-Perot modes inside the cavity. Interactions among them lead to a series of hybridized eigenmodes exhibiting excellent spectral tunability and spatially distinct field distributions, which cannot be achieved by convential grating photocoupler. As an example, we design a two-color detector protocol with calculated photon absorption efficiencies enhanced by more than 20 times at both colors, reaching ~42.8% at 15μm (in wavelength) and ~46.2% at ~10.2 μm for a 1 μm total thickness of sandwiched quantum wells. The rich plasmonic-photonic hybridization effects discovered here provide plenty of opportunities to optimize light harvesting efficiencies for modern ultra-small infrared optoelectronic devices with subwavelength dimensions.

9160-92, Session PWed

Reflected metasurface for polarization-controlled hologram application

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Holograms are the optical devices that are able to reconstruct pre-designed images and show many applications in our daily life. However, applications of hologram are always limited by the constituent materials and pixel sizes resulting in the working range are forbidden at particular wavelength region. In recent years, the metasurfaces, an array of plasmonic antenna with varying geometric sizes showing the abilities to manipulate both amplitude and phase of incident electromagnetic wave in a wide electromagnetic region. Here, we present a hologram composed of reflected metasurface (called meta-hologram) which is designed and fabricated for visible wavelength. Also, both experimental and simulation results show the meta-hologram working in a very high efficiency. Using gold cross nano-antennas as building pixel to construct our meta-hologram devices, the reconstructed images of meta-hologram show polarization-controlled dual images with high contrast for both coherent and incoherent light sources. Moreover, such meta-hologram not only shows a broad spectral working range but also under a wide range of incidence angles. The flexibility demonstrated here for our meta-hologram paves the road to a wide range of applications related to holographic images at arbitrary electromagnetic wave region.

9160-93, Session PWed

Calculating magnetic permeability response from a conducting square ring structure

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Recently, there have been some suggestions to utilize the non-resonant elements to get a diamagnetic response with permittivity less than one over a wide frequency range. Actually, enhancing the diamagnetic interactions between theses loops leads to a rise of the magnitude of the mutual inductance and in turn the magnitude of the magnetic susceptibility of the system. In this paper, the properties of an arrangement of periodically conducting square rings have been characterized. The core of this numerical work is to analyze the inductive interactions between the building blocks. A lattice model has been introduced in order to determine the magnetic permeability of the structure from the microscopic quantities which are the total mutual inductance and capacitance of the entire construction plus the self-inductance of individual cells. Frequency dispersion of the magnetic permeability is due to the self-inductance of individual square ring. Despite the fact that this effect is not as dominant as resonant processes in split-ring resonators, this approach introduces a magnetic response with a broad-band frequency.

It is also demonstrated that the general behavior of the circular and square ring architecture is the same. However, in order to obtain the closest packing pattern, which leads to stronger mutual inductance, the square ring formation is the best choice. As a matter of fact, square pattern has no magnetic flux loss if its thickness is ignored (ideal case).

9160-94, Session PWed

Nonreciprocal manipulation of light propagation in 2D-photonic crystals with cylindrical metamaterials consisting of arrayed SWNTs with helical DC

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The nonreciprocal manipulation of light propagation is an invaluable ingredient in a next-generation optical networking. However, it is challenging to bend a photon's path rapidly even by using magnetized dielectrics which is only natural nonreciprocal materials. The purpose of this contribution is to introduce a novel material structure to achieve the above mentioned challenging goal.

First, we demonstrate the TE light propagation in nonreciprocal cylindrical 2D-photonic crystals whose dielectric tensor has real parts of off-diagonal terms. In whispering gallery mode (WGM) in each unit element, light goes around one-way direction of the circumference of a cylinder, and resonates nonreciprocally with the periodic array of cylinders. As a result, the direction of light propagation becomes round and the nonreciprocal degree is dominated by the real parts of off-diagonal terms of the dielectric tensor.

On the other hand, the real parts of off-diagonal elements are always associated with the large imaginary parts of diagonal terms, which ensures no energy divergence. However, this spoils the effect of WGM.

Then, we introduce a novel phenomenon to overcome the above problem, i.e., rotational Doppler shift in helical conducting SWNTs. If the angular frequency of electrons of helical currents is larger than the light frequency, the amplitude of one circular polarization is intensified. So the effective-dielectric tensor has large real parts of off-diagonal terms.

As a result, 2D-photonic crystals with cylindrical metamaterials consisting of arrayed SWNTs with helical DC enable us to manipulate light propagation in a drastic way.

9160-96, Session PWed

Scattering and coupling between subwavelength resonators

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Understanding the mechanisms behind novel electromagnetic properties of metamaterials is crucial to design better structures; so we study how meta-atoms interact with each other depending on the periodicity of the structure. We investigate how energy coupling occurs between different resonant frequencies of our designed subwavelength meander type resonators and how it defines the bulk properties. To do this, we start with numerical simulations of a small number of meta-atoms to see how coupling changes by changing the number of subwavelength resonators. In addition, we compare the simulation results with experiments done in the microwave region. Furthermore, we study some of bulk properties such as negative refraction where how periodicity and scattering of subwavelength elements influence it, whether there is negative index or not. A prism made out of our designed S-resonator was simulated to show the existence of negative refraction and to understand its relation with negative index.

9160-97, Session PWed

Enhanced radiation from dipolar sources in proximity of subwavelength hyperbolic metamaterial resonators

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Hyperbolic material (HM) substrates are shown to increase dramatically the power emitted by dipolar emitters in their proximity due to the increased local density of states. In general most of the emitted power by a dipolar source is coupled to the HM substrate and dissipated there as heat. This fact can be used for engineering the decay rate of emitters whereas the emitted power into the free space is not enhanced necessarily and the radiation efficiency of such systems remains low. On the other hand, for many applications such as solid-state lighting, the main goal is to achieve the enhancement of radiative emission, instead of just boosting the total emission. In this study we utilize three-dimensional HM resonators with subwavelength size for enhancing not only the Purcell factor, but also the radiative emission of a quantum emitter positioned close to the resonator. Resonators are made of silver-silica layers. Our findings indicate that the total emission is enhanced mainly due to the increased radiation into free space showing that HM resonators are efficient radiators and suitable for utilization as nano-antennas. Various dipole positions and orientations are investigated and at the resonance wavelength in the visible spectrum we report up to 100-fold enhancement of radiative power emission with respect to the power emitted by a dipole in free space. Finally we elaborate on the impact of using a finite array of HM resonators stressing the role of inter-element spacing. In summary, we report that a dense array of subwavelength HM resonators can be used for enhancing radiative emission of quantum emitters.

9160-98, Session PWed

Plasmonic color filters to decrease ambient light errors on active type double band infrared image sensors

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We proposed plasmonic color filters for active type double band infrared image sensors to decrease ambient light errors. To design the plasmonic color filters we executed a computer simulation utilizing finite-difference time-domain (FDTD) method. We also described the mechanism applied the double band color filter on the IR image sensors.

9160-99, Session PWed

Characterization of ferromagnetic/dielectric systems for metamaterials applications

Brittany Bates, Nicole Greene, Natalia Noginova, Norfolk State Univ. (United States)

Incorporation of ferromagnetic materials into metamaterial systems provides an opportunity to tune microwave permeability with an external magnetic field, strongly affecting wave propagation. We characterize microwave properties of several soft magnetic materials with high permeability as possible candidates for such applications. In the range of the ferromagnetic resonance, the permeability of ferromagnetic/dielectric composites varies from positive to negative values. In addition, a low field absorption peak is observed in mu-metal and metglas systems. This feature can be ascribed to the domain mode resonance, which provides an additional possibility of tuning with low fields.

9160-100, Session PWed

Anisotropy modeling of polarization dependent terahertz metamaterials

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There have been substantial progresses in engineering the resonance properties of metamaterials by manipulating the size, pitch, or shape of their meta-atoms to be utilized for the terahertz and optical applications such as filters, detectors, sensors, and absorbers. It is well known that most of metamaterials have different resonance properties depending on the polarization of incident waves. However, any comprehensive study for understanding the resonance mechanism by the anisotropy of metamaterials has never been reported so far. In this study, we propose a novel anisotropy modeling of the polarization dependent meta-atoms at terahertz frequencies. The proposed anisotropic metamaterials are composed of metallic microstructures combined with various numbers of H-shaped meta-atoms and fabricated onto the flexible polyimide substrate by conventional photolithography process. We confirm that the proposed metamaterials successfully realize the unique properties that can modulate the resonance frequency for the specific polarization of an incident wave, while can keep one identical resonance frequency for their orthogonal polarization direction, simultaneously. Moreover, the experimental results show that regardless of the number of H-shaped meta-atoms as well as the polarization direction, their individual bandwidth can stay unchanged by coupling effects between adjacent meta-atoms and their excited electric dipole moments. Since the complementary structure has the opposite properties due to Babinet's principle, the proposed design methods are expected to be utilized not only for the reflective type, but also for the transmissive type metamaterial filters.

9160-101, Session PWed

Excitation of surface waves in the photonic crystal / graphene structure for terahertz frequency range

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Photonic crystals are one of the most remarkable metamaterials for electromagnetic waves manipulation for last decades, therefore they can be used as filters, waveguides, polarization changers, superlenses, superprisms, etc [1]. As well today graphene has attracted considerable attention due to the unusual properties such as perfect thermal and electric conductivities etc. [2]. A periodic stack of equally spaced parallel layers of graphene has the properties of a 1D photonic crystal, with narrow stop bands that are nearly periodic in frequency, and that may be used as spectral-selective mirror [3]. In this paper the excitation of surface waves in the photonic crystal bounded by graphene layer was investigated for terahertz frequency range. Peaks of transmissivity in band-gaps of photonic crystal that caused by excitation of surface waves were obtained. The control of frequency position of peaks by temperature and magnetic field was demonstrated in the frequency range from 0.1 to 1 THz.

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9160-103, Session PWed

Titanium nitride as nonmetallic metamaterial component: gyroidal self-assembly and nonlinear optical response

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Titanium Nitride (TiN) is considered to be a non-metallic alternative to traditional (gold and silver) plasmonic materials. In this work, we have studied (1) nonlinear chi3 optical response of TiN thin films (using z-scan technique) as well as (2) optical properties of the gyroidal metamaterial assembled of TiN nanoparticles. Despite of relatively low plasmonic response of TiN gyroidal metamaterial, some of its properties (e.g. bright multi-color reflection observed in optical microscopy) resemble those of gyroidal metamaterial composed of Au nanoparticles.

9160-72, Session 15

Microwave interaction with visible light

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We report an arrangement allowing interaction between waves of arbitrary frequencies, which is achieved by introducing an additional coupling mechanism to impose artificial interaction between otherwise independent elements.

We provide a scheme where split-ring resonators (SRRs) are actively involved in the optical control, serving as both receivers and sources of optical radiation. Our design comprises two varactor-loaded SRRs, which are arranged to be orthogonal to each other. With this geometry, the symmetry of the arrangement ensures there is no electromagnetic coupling between the two resonators. However, one of the SRRs is controlled by a photodiode (PD), and the other is equipped with a light-emitting diode (LED), positioned so as to provide efficient optical interaction between the LED and the PD. At low power of the electromagnetic signal launched into the LED-SRR, there is insufficient voltage rectified by the varactor to light up the LED, so there is no interaction between the SRRs. At higher power, the LED is lit and the emitted light is absorbed by the PD, providing a voltage across the varactor, thus changing its capacitance, which directly affects the resonance frequency of the PD-SRR. Thus, the resonant frequency of the PD-SRR is directly controlled by the signal power in the LED-SRR, despite having no direct electromagnetic coupling between the two.

We report a prototype fabrication and experimental confirmation of the above ideas, demonstrating a remarkable resonance shift and polarisation dependence.

9160-73, Session 15

Backward phase matching for second harmonic generation in negative index materials

Wenshan Cai, Georgia Institute of Technology (United States)

The phase-matching condition, resulting from the conservation of photon momentum, is among the foremost vital aspects to consider in harmonic generation and wave-mixing. The exotic electromagnetic parameters made possible by metamaterials provoke us to reevaluate the established rules of phase-matching for nonlinear optical interactions. When a metamaterial possesses a positive index of refraction at the fundamental frequency and a negative index for the harmonic wave, phase-matched frequency doubling requires that the indices for the fundamental and harmonic waves have the same magnitude but opposite signs. Since the Poynting vector and the wave vector in a negative-index medium are antiparallel to each other, the harmonic output will travel towards the source of the fundamental wave. This new type of phase-matching condition, known as "backward phase-matching," has been predicted for years but an experimental verification at optical frequencies is still lacking.

Here we report the experimental demonstration of backward phase matching in a negative index material. The unconventional phase matching condition is achieved by exploiting two distinct modes in a plasmonic waveguide, where the real parts of the refractive indices is 3.4 and -3.4, respectively, for the fundamental wave at 770nm and the harmonic at 385nm. The effective, nonvanishing second-order nonlinear susceptibility is enabled by applying a bias voltage across half of the dielectric layer in the waveguide. The observed peak conversion efficiency at the excitation wavelength of ~770nm indicates the backward phase matching, where the phase-matched harmonic wave propagates along a direction opposite to that of the incoming fundamental wave.

9160-74, Session 15

From unidirectional scattering to nonlinear unidirectional generation: leveraging magneto-electric interference

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We analyze the resonant electromagnetic response of sub-wavelength plasmonic dimers formed by two metal strips separated by a thin dielectric spacer. We demonstrate that the off-resonant electric and resonant, geometric shape-leveraged, magnetic polarizabilities of the dimer element can be designed to have close absolute values in a certain spectral range, resulting in a predominantly unidirectional scattering of the incident field due to pronounced magneto-electric interference. Switching between forward and backward directionality can be achieved with a single element by changing the excitation wavelength, with the scattering direction defined by the relative phases of the polarizabilities.

We consider further the nonlinear response of dimers to electromagnetic excitation. We demonstrate that, similar to the linear case, a unidirectional nonlinear generation is possible by leveraging magneto-electric interference in the nonlinearly produced field, without phase-matching requirements being involved. The nonlinear regime gives an additional advantage of achieving unidirectional generation for the total (nonlinearly produced) field, rather than just for the scattered portion of the field. Moreover, a proper choice of the crystalline properties of the spacer material can lead to nonlinear generation predominantly in the direction orthogonal to that of the original excitation, in case of a single isolated dimer.

We next extend the analysis to some periodic configurations, including the specific case of a perforated metal film, and discuss the differences between the observed unidirectional scattering and the extraordinary transmission effect. The unidirectional response can be preserved and enhanced with periodic arrays of dimers and can find applications in nanoantenna devices and integrated optic circuits.

9160-75, Session 15

Second harmonic generation from asymmetric plasmonic nanoparticle dimers

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In this paper we explore the second-order nonlinear response of the pairs (dimers) of plasmonic nanoparticles possessing a localized surface plasmon resonance (LSPR). Significant effort has been devoted to exploring the interaction between plasmonic nanoparticle assemblies and strongly interacting nanoparticles. The linear properties of such systems have been the focus of much recent work. Following on this, we focus on the nonlinear response of interacting particle assemblies both theoretically and experimentally. In these assemblies, despite even-order nonlinear processes being forbidden in bulk centro-symmetric medium like metals, we predict a high degree of resonant enhancement for pairs of spherical shaped nanoparticles where inversion symmetry is broken by an asymmetry in particle size. Recent experiments demonstrate a significant second-harmonic surface nonlinear response from the local fundamental field distribution and enhancement present in dimer assemblies. We explore different configurations of nanoparticle dimers ranging over shape, size and separation by performing calculations on experimentally relevant systems. This allows us to draw from and compare existing studies of particle pairs and target new studies on high second harmonic yield configurations. Nonlinear measurements of second harmonic yield from selected configurations prepared by directed self-assembly techniques will be presented. Our calculations, carried out accounting for high multipolar orders of interaction, demonstrate that the optical response of dimers exhibits a periodic dependence on the distance between nanoparticles, and that this becomes more pronounced for more asymmetric pairs.

9160-76, Session 15

Electrically controlled nonlinear optical phenomena in photonic metamaterials *(Invited Paper)*

Wenshan Cai, Georgia Institute of Technology (United States)

The past decade has witnessed the emergence and explosive development of optical metamaterials that afford exotic light manipulations. In addition to the continued investigation of these artificially structured optical media with unorthodox properties not found in nature, there has been an ever-growing interest in the study of metamaterials beyond the conventional, linear regime. Two particularly compelling directions are active metamaterials, where the optical properties can be purposely tailored by external stimuli in a reversible manner, and nonlinear metamaterials, which enable intensity-dependent frequency conversion of light waves. By exploring the interaction of these two directions, in this work we leverage the electrical and optical functions simultaneously supported in nanostructured metals and experimentally demonstrate electrically-controlled nonlinear optical processes from a metamaterial absorber. Both the second harmonic generation and the optical rectification, enhanced by the light concentrating ability in the tri-layered metal-dielectric structure, are shown to follow the resonance behavior in the metamaterial and are modulated externally with applied voltage signals. Our results reveal the potential of metamaterials as customized nonlinear media with engineered and intercorrelated linear and higher-order properties. These results also demonstrate the grand opportunity to exploit optical metamaterials as a self-contained, dynamic electrooptic system with intrinsically embedded electrical functions and optical nonlinearities.

9160-77, Session 15

Subpicosecond relaxation of the third-order nonlinear susceptibility in fishnet metamaterials

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To date, much effort was put in experimental studies of optical properties of fishnet metamaterials. However, experiments on their nonlinear-optical properties are largely limited to the optical harmonic generation spectroscopy. In this work, we study the temporal dynamics of the third-order nonlinear susceptibility in fishnet metamaterials on the subpicosecond time scale using the pump-probe technique.

The sample was made by e-beam-lithography and lift-off techniques. It represents a multilayer Au-MgO-Au heterostructure. The structure has a period of 500 nm in both lateral directions. The thicknesses of the Au films and the intermediate dielectric film are 20 nm and 35 nm, respectively. Transient properties of third-order optical nonlinearity are probed using the pump-probe technique. Two femtosecond laser pulse trains from an Er-doped passively mode-locked fiber laser are focused by an objective lens onto the sample. The third harmonic generation signal is collected behind it by a photon-multiplier tube. Inducing a time delay between the pulses makes it possible to observe non-stationary states of the nonlinear susceptibility of the sample.

Experimental data indicate existence of a delay in the nonlinear response of the metamaterial attributed to subpicosecond relaxation of gold characterized by a time constant of approximately 1 ps. Estimated modulation of the third-order nonlinear susceptibility is equal to 5% for a pump pulse energy of 120 fJ.

Our results disclose the possibilities of tailoring the nonlinear-optical properties of the fishnet metamaterials on the subpicosecond time scale.

9160-78, Session 16

THz polarization control using chiral metamaterials *(Invited Paper)*

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Chiral metamaterials, due to their giant chirality values, orders of magnitude larger than the chirality of natural chiral materials, can provide unique possibilities for the control of electromagnetic wave polarization. Such a control is extremely useful in the THz regime, where there is a serious lack of optical components. In this talk we will present a variety of different chiral metamaterials operating in the THz regime and we will demonstrate, both theoretically and experimentally, very large optical activity values and/or large circular dichroism and/or negative refractive index response, verifying thus the unique capabilities of our metamaterials to control the THz-wave polarization. Moreover, incorporating properly in our metamaterial structures photoconducting Si, we demonstrate optically switchable chiral response, which gives to our structures a unique potential to create dynamic polarization control components, like switchable polarization filters, modulators, wave plates and others.

9160-79, Session 16

Theory and modeling of self-induced transparency in Terahertz graphene metamaterials *(Invited Paper)*

Sang Soon Oh, Joachim M. Hamm, Andreas Pusch, Ortwin Hess, Imperial College London (United Kingdom)

The optical conductivity of graphene can be described as a sum of intraband and interband conductivities. When doped, graphene will have a non-zero Fermi level such that the intraband conductivity is dominant at terahertz frequencies, but it can be significantly reduced by strong incident electromagnetic waves allowing high transmission. Undoubtedly, this induced transparency of graphene can be modified by changing the gate voltage or by overlaying metamaterials on graphene. However, it is not straightforward to explain the induced transmission change – self-induced transparency – of graphene metamaterials for different incident field intensities, since a modified optical conductivity and an associated non-uniform field distribution are present and involved simultaneously. To understand the underlying physics of induced transparency of graphene metamaterials at terahertz frequencies, we performed numerical simulations based on the finite-difference time-domain method incorporated with an analytical model for the optical conductivity of graphene. Our simulation results confirm that the induced transparency of graphene metamaterial is strongly dependent on both the gate voltage and the geometry parameters of meta-atoms. We show that the resonant nature of graphene metamaterials significantly modifies the induced transparency of graphene. In particular, the sign of the modulation depth (T/dT) is reversed at the resonant frequencies of metamaterials. We employed a simple RLC model to explain the reversed sign and this is supported by FDTD simulation results. In addition, the effect of non-uniform electric field on the induced transparency is investigated. We believe that our model will provide a simple way of understanding the nonlinear response of graphene metamaterials.

9160-80, Session 16

Manipulating terahertz waves with photo-imprinted diffraction gratings

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The terahertz spectral range of the electromagnetic spectrum—loosely defined from about 100GHz to 10THz—has long been an inaccessible region in between the successful realms of electronics and photonics, because of the lack of efficient and compact sources and detectors for terahertz radiation. Developments in the past decade, however, have enabled the exploration of terahertz science and the rapid rise of terahertz imaging and spectroscopy for, amongst others, biomedical and security applications. Here we explore a route towards reconfigurable terahertz devices. We demonstrate the possibility of creating photonic structures for terahertz waves by projecting the optical image of a metal mask onto a thin GaAs substrate using a femtosecond pulsed laser source [Appl. Phys. Lett. 103, 043101 (2013)]. This creates a pattern of illuminated and dark regions on the substrate. We show that the conductive pattern of free carriers created in this way behaves like a diffraction grating for terahertz waves and we present examples of one- and two-dimensional gratings. The experimental results are confirmed by computer simulations. The demonstrated photo-imprinted diffractive elements could be made reconfigurable by replacing the fixed metal mask employed in our study by a device with spatially controlled transmission for the optical pump beam, e.g., a digital micromirror device.

9160-81, Session 16

Design, simulation, and fabrication of a novel reconfigurable graphene terahertz filter

Kai Yang, Sara Arezoomandan, Berardi Sensale-Rodriguez, The Univ. of Utah (United States)

Graphene is an allotrope of carbon atoms arranged in a two-dimensional honeycomb lattice structure. Single-layer graphene has excellent electrical, thermal, mechanical, and optical properties, which makes it attractive for many terahertz applications. Terahertz waves can be employed in diverse areas such as astronomy, security, high speed communications, biomedicine, spectroscopy, etc. However, up until recently, there has been a lack of practical terahertz active devices such as reconfigurable terahertz filters. Many of these applications require the development of simple reconfigurable terahertz filters to control and manipulate terahertz waves. Taking advantage of the extraordinary properties of graphene, we propose and discuss a novel micro-machined reconfigurable graphene-based terahertz filter. The key components are the periodic metal rings with several gaps where active graphene strips are placed. We can easily adjust the resonance frequency of the terahertz filter by varying a couple of parameters such as the inner and outer radius of the metal ring, the gap, the number of graphene layers, and by (dynamically) varying the conductivity of each graphene layer. This work explains the principle of operation of the device, its design based on numerical simulations, its fabrication process, and also presents experiment results. The simulation results show that the resonance frequency is a monotonically decreasing function of the graphene electrical conductivity. The active area is also an important parameter in graphene terahertz devices as reducing it can boost the speed of the device. This device's active area is >100X smaller than that of other devices proposed in the literature.

9160-82, Session 16

Tunable frequency converter for terahertz frequency range based on space-time transformation

Egor A. Gurvitz, Anna V. Vozianova, Mikhail K. Khodzitskiy, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Recently, special interest is being shown to developments of media with space-time dependent dispersion of constitutive parameters. The physical principals of such media [1] can be effectively described in the frame of transformation optics theory [2]. In general, potential applications of such media can be found in laser system devices, fiber optics transmission lines, radars and detection systems, integrated and planar optics and etc. In this paper, tunable frequency convertor medium on basis of transformation optics theory was considered. It can be used as a source of tunable frequency generation in radar, spectroscopy and imaging systems. The tunable frequency convertor can be realized by using metamaterials with time dependent permittivity and permeability which are modulated by high speed arbitrary signal form generator. In this work we present analytical and numerical investigation of such device and consider metamaterial constitutive parameters for conversion of infrared radiation into terahertz one.

[1] Ginis, V., Tessin, Ph., Craps, B., Veretennicoff, I.,"Frequency converter implementing an optical analogue of the cosmological redshift", OPTICS EXPRESS 5350, Vol 18, No.5 (2010)

[2] Ulf Leonhardt and Thomas Philbin, [Geometry and Light], Dover Publications, Dover Books on Physics, (2010)

9160-83, Session 17

Polarization controlled colorful images reconstructed by reflective meta-hologram *(Invited Paper)*

Din Ping Tsai, Academia Sinica (Taiwan); Pin Chieh Wu, Wei Ting Chen, National Taiwan Univ. (Taiwan); Kuang-Yu Yang, Academia Sinica (Taiwan); Chih-Ming Wang, National Dong Hwa Univ. (Taiwan); Yao-Wei Huang, National Taiwan Univ. (Taiwan); Greg Sun, Univ. of Massachusetts Boston (United States); Shulin Sun, Lei Zhou, Fudan Univ. (China); Ai Qun Liu, Nanyang Technological Univ. (Singapore)

Holograms are the optical devices to reconstruct images by recovering amplitude and phase of light, which show many applications in our daily life. Recently, the metasurfaces, an array of sub-wavelength antenna, show the abilities to exhibit extraordinary light-manipulation abilities to overcome the limitations of conventional holograms, such as the absorption of photo-sensitive material or the pixel size of hologram. Here, we performed a high-efficiency broadband reflected metasurface and meta-hologram in 4-level phase by reflected metasurface made of subwavelength 6x6 gold cross nano-antennas of 16 different shapes which is designed and fabricated in optical frequencies. As a result, the reconstructed images of meta-hologram exhibit far more efficient (reaches 18% for 780 nm illumination), polarization-controlled dual colorful images with high contrast, functioning for both coherent and incoherent light sources within a broad spectral range (bandwidth ?880 nm) and under a wide range of incidence angles. The reflective hologram has a number of advantages such as simple fabrication process, low metal absorption, broad working spectral range, and greater tolerance to variation of incident angle and light incoherence. By combining with the techniques of tunable metasurfaces, meta-hologram can potentially be used to realize the active hologram that works at arbitrary electromagnetic wave region.

9160-84, Session 17

Numerically stable reconstruction of wavelength-scale objects with sub-wavelength resolution

Sandeep Inampudi, Univ. of Massachusetts Lowell (United States); Nicholas A. Kuhta, Oregon State Univ. (United States); Viktor A. Podolskiy, Univ. of Massachusetts Lowell (United States)

Significant developments in materials and fabrication techniques require development in imaging systems in order to resolve sub-wavelength details of objects. So far the only reliable technique to provide nano-scale resolution is near field scanning optical microscopy (NSOM) which relies on point-by-point scanning and has other complications. In contrast, engineered meta-grating structures (optically thin gratings with sub-wavelength periodicity) have the ability to couple and transmit information about the sub-wavelength features of the near-field object to propagating waves have shown promising results in resolving sub-wavelength features with far-field measurements. Implementation of this technique relies on computational image reconstruction using multiple far-field measurements and requires a parametric representation of spatial spectrum of the object. However, classic expansions including Taylor and orthogonal-function-based series result in substantial instabilities in recovery of higher wavevector part of the spectrum. Here we present a highly stable and accurate image recovery process using physically meaningful expansion into "pixel" basis. In this expansion, the area covered by the illumination beam is divided into a finite number of regions (pixels) and the intensity produced by the object at the location of each pixel is numerically recovered. Our results indicate that in ideal situation with higher signal-to-noise ratio the technique can provide resolutions of the order of wavelength/50, while in a more realistic setting

the technique can achieve stable image recoveries with resolution of the order of wavelength/20, far better than resolutions of any far-field imaging techniques to date.

9160-85, Session 17

Invisibility cloaking in the diffusive-light limit *(Invited Paper)*

Robert Schittny, Muamer Kadic, Martin Wegener, Karlsruher Institut für Technologie (Germany)

Albert Einstein's theory of relativity imposes stringent limitations to making macroscopic objects invisible with respect to electromagnetic light waves propagating in vacuum. These limitations are not relevant though for propagation of light in diffusive media like fog or milk because the effective energy speed is significantly lower than in vacuum due to multiple scattering events. Here, by exploiting the close mathematical analogy between the electrostatic or near-field limit of optics on the one hand and light diffusion on the other hand, we design, fabricate, and characterize simple core-shell cloaking structures for diffusive light propagation in cylindrical and spherical geometry.

In our experiments, a hollow metallic core with few-centimeters radius and effectively zero diffusivity isolates its interior from the outside. To make this core appear like the diffusive surrounding, we add a shell with higher diffusivity than that of the surrounding. Formulas connecting the required radii and diffusivities can immediately be translated from the electrostatic limit of optics. The shell is implemented by a polydimethylsiloxane (PDMS) coating, doped with dielectric melamine-resin microparticles. The surrounding is water with some milk or other scattering medium added. Following white-light illumination from one side, we image the light emerging on the other side. While the obstacles alone cast a significant diffusive shadow, the cloaks nearly appear like the homogeneous surrounding without anything inside.

9160-86, Session 17

Design of homogeneous coatings for the cloaking of arbitrarily-shaped objects

Carlo Forestiere, Luca Dal Negro, Boston Univ. (United States); Giovanni Miano, Univ. degli Studi di Napoli Federico II (Italy)

We present a novel theory for the cloaking of arbitrarily-shaped objects and demonstrate electromagnetic scattering cancellation through designed homogeneous coatings. Our approach is based on the quasi-electrostatic approximation and on its first and second order radiative corrections, obtained through the perturbation theory. By expanding the dipole moment of a coated object in terms of its resonant modes, we perform the direct calculation of the permittivity values of the coating layer that cancel the net dipole moment and abates the total scattered power. In particular, this is accomplished by finding the the zeros of a polynomial, whose degree depends on the number of bright modes of the system. We also show that, by using the radiative corrections, our approach leads to an accurate design of the cloaking not only in the Rayleigh limit, but in the whole regime in which the dipolar scattering is dominant. Finally, we present several examples of the cloaking of arbitrarily-shaped object, of particles lying on a substrate, and of multi-coated objects. The developed approach paves the way to the the design of ``invisibility cloaks" for irregularly-shaped devices such as complex sensors and detectors.

9160-87, Session 17

Optimization of aberrations in transformation optics inspired lenses

Saul Wiggin, Queen Mary, Univ. of London (United Kingdom)

A new optical lens is designed using metamaterials and transformation optics based on the Cooke triplet. The original lens system was defined using ray tracing in standard optical design software, while a single lens has been constructed to 'mimic' its performance. We find the proposed lens has preserved properties from its triplet counterpart with improved RMS wavefront.

9161-2, Session 1

A new and fast numerical method for the determination of the optical properties of quantum structures

François Thierry, Judikaël Le Rouzo, Institut Matériaux Microélectronique Nanosciences de Provence (France); François R. Flory, Institut Matériaux Microélectronique Nanosciences de Provence (France) and Ecole Centrale Marseille (France); Gérard Berginc, Thales Optronique SA (France); Ludovic Escoubas, Institut Matériaux Microélectronique Nanosciences de Provence (France)

We present a novel numerical method to determine the optical properties of nanostructures. The structures under study are quantum wells (QWs), circular cross-section quantum wires (QWRs) and spherical quantum dots (QDs). The properties that we focus on are absorption, photoluminescence and effective refractive index. We calculate the energy levels with a new formulation of a shooting method under the envelope function and effective mass approximations with a band nonparabolicity correction. Although the effective mass approximation has been proven to diverge for small sizes and low-bandgap materials, we show that we can achieve great correlation with results of semiempirical methods such as pseudopotential (PP), tight-binding (TB), k.p or even ab-initio calculations such as local-density approximation (LDA) taken from the literature. This allows a more accurate determination of the optical properties that derive from electronic ones. We especially study the impact of the size on confinement effects. The model that we use is fast, that is why it has a great interest for optimization procedures. This could be used to estimate the power conversion efficiency of next generation solar cells that incorporate nanostructures and find the best combination of components and structural geometries to get the optimum device design.

9161-3, Session 1

Influence of core-shell interfaces in exciton and multi-exciton dynamics of CdSe-CdZnS quantum dots

Alessandro Minotto, Francesco Todescato, Raffaella Signorini, Univ. degli Studi di Padova (Italy); Jacek J. Jasieniak, Commonwealth Scientific and Industrial Research Organisation (Australia); Renato Bozio, Univ. degli Studi di Padova (Italy)

Semiconductor quantum dots (QDs) possess attractive optical properties that fulfill different tasks in photonics. Thanks to the evolution of core-shell colloidal synthesis[1], QDs exhibit almost ideal emitting properties. Their employment in optoelectronic devices is encouraged by their size-tunable emission as well as by their high absorption cross-sections and high photoluminescence (PL) quantum yields (QYs)[2,3]. In this work, starting from the archetypal CdSe based systems, the influence of shell thickness and composition on exciton dynamics in CdSe-CdxZn1-xS core-shell QDs is investigated. By means of steady-state (Uv-Vis absorption, PL, amplified PL) and transient optical spectroscopy (PL and pump-probe), single- and multi-exciton creation and recombination processes are characterized and correlated with different core-shell interfaces, previously studied with a Raman experiment4. Surface trap states are responsible for single QD PL blinking and Auger non-radiative recombination, which strongly hamper the generation and the radiative recombination of excitons and multi-excitons, respectively. The variety of spectroscopic techniques employed permit to explore the interaction between exciton and trap-states from picosecond to hundreds of nanoseconds time scale. The present study clarifies why graded core-shell CdSe-CdS-Cd0.5Zn0.5-ZnS represent the best performing hetero-structure, since such QDs combine the high radiative rates of CdS, the efficient de-trapping process of Cd0.5Zn0.5S and the superior confinement potential of ZnS in a single dot.

[1] Lieber C M, 2003 MRS Bull. 28 486
[2] Qu L. and Peng X. G. 2002 JACS, 124, 2049
[3] Todescato F. et al. 2012 Adv. Mater. 22 337
[4] Todescato F. et al. 2013, ACS Nano 7 6649

9161-4, Session 1

Investigation of CdS nanowire lasing emission

Robert Röder, Max Riediger, Friedrich-Schiller-Univ. Jena (Germany); Daniel Ploss, Arian Kriesch, Robert Buschlinger, Ulf Peschel, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Carsten Ronning, Friedrich-Schiller-Univ. Jena (Germany)

Nanophotonic on-chip integrated components are a promising approach to face forthcoming limitations of electronic integrated circuits by new all optical concepts using optical data transmission and processing. Exploiting semiconductor nanowires, which offer efficient waveguide properties and mark the lower size limit of photonic laser systems, builds a possible route to overcome these challenges. High quality cadmium sulfide nanowires open therefore up the green spectral range around 2.4 eV acting as Fabry-Pérot laser resonators with a remarkable low threshold of 10 kW/cm^2 at room temperature [Geburt et al, Nanotechnology 23, 365204 (2012)] and operating even in cw emission mode [Röder et al, Nano Letters 13, 3602 (2013)]. Since optical processing is depending on the emission characteristics of the future device, a "head-on" setup was developed to investigate the light output originating out of the end facet of a single nanowire laser. This setup is suited to investigate super luminescence (ASE) as well as lasing emission as a function of the polarization of the optical pump beam. Furthermore, the angular distribution of nanowire lasing emission as well as the polarization can be determined.

9161-5, Session 1

Engineering bright sub-10-nm upconverting nanocrystals for single-molecule imaging *(Invited Paper)*

Emory Chan, The Molecular Foundry (United States)

Lanthanide-doped nanocrystals can be utilized as low-background biological imaging probes due to their ability to convert infrared excitation into visible emission – a process known as upconversion. These unique upconverting probes do not photobleach or decompose under intense excitation, enabling their use in long-term studies and single-molecule assays. The brightness of these lanthanide-doped particles, however, has been limited by a poor understanding of energy transfer within the nanocrystal and an unavoidable trade-off between brightness and size. Here, we describe the use of a high-throughput computational package to simulate the spectrum and energy transfer pathways of arbitrary compositions of NaYF4 nanocrystals doped with multiple lanthanide ions. Using this in silico combinatorial method, we screened for nanocrystal compositions that exhibit high luminescence intensity and high spectral purity. These hits were then experimentally refined using a high-throughput nanocrystal synthesis robot and a laser-scanning plate reader. Finally, we used single-nanoparticle upconversion microscopy to investigate the effects of surfaces on the upconverted emission of a size series of nanocrystals. This combined theoretical and experimental approach allowed us to predict and experimentally verify new compositions of upconverting nanocrystals that are brighter and more spectrally pure than previous nanoparticles, enabling the imaging of single upconverting nanoparticles as small as fluorescent proteins.

9161-6, Session 2

Novel materials and nanostructures for near-field engineering *(Invited Paper)*

Luca Dal Negro, Boston Univ. (United States)

The development of novel Si-compatible materials and nanostructures that support optical resonances with strongly enhanced local fields enables the control of propagating and non-propagating electromagnetic fields for the engineering of plasmonics and metamaterials components that can be easily integrated within the current CMOS technology. In this talk, I will present our results on the materials development and nanofabrication of active nanostructures based on low-loss conductive oxides with tunable negative permittivity in the near-infrared spectral range. In particular, I will discuss our recent work on rare-earth doping of conductive oxide nanostructures and metamaterials that boost polaritonic responses across the 1-2 µm spectral range on a Si compatible platform.

In this talk, I will present our results on the materials development and nanofabrication of light emitting and strongly nonlinear active nanostructures based on low-loss conductive oxides with tunable negative permittivity in the near-infrared spectral range. In particular, I will discuss our recent work on rare-earth doping of conductive oxide nanostructures and metamaterials to boost polaritonic responses across the 1-2 µm spectral range.

9161-7, Session 2

Surface-enhanced infrared spectroscopy using metal oxide plasmonic nanoantennas

Otto L. Muskens, Yudong Wang, Martina Abb, Cornelis H. de Groot, Univ. of Southampton (United Kingdom)

Metal oxides are technologically important materials for use in catalysis, electronics, and sensors. We demonstrate strong surface enhanced infrared spectroscopy (SEIRS) using metal oxide plasmonic nanoantennas. Using a deposition process compatible with e-beam lithography and lift-off, we have fabricated of indium-tin oxide antennas of varying length ranging between 0.2 - 4.0 micrometers [1]. FTIR spectroscopy of antenna arrays was used to demonstrate effective the wavelength scaling and a fourfold reduction of the plasmon wavelength, enabling ultracompact antennas and extremely subwavelength metamaterials. The SEIRS signal of a 50-nm thin film of PMMA spincoated over the antennas was used to demonstrate the near-field enhancement associated with the plasmonic antennas [1]. The response of the ITO arrays was of comparable strength as equivalent arrays of gold antennas. We subsequently demonstrate extremely high density integration of ITO and gold antennas with spacings as small as 100nm, entering the range of plasmonic near field coupling. The plasmonic functionality of doped metal oxides complements existing applications of these versatile materials and may open up new applications in mid-IR spectroscopy and sensing.

[1] M. Abb, Y. Wang, N. Papasimakis, C. H. de Groot, O. L. Muskens, Surface-Enhanced Infrared Spectroscopy Using Metal Oxide Plasmonic Antenna Arrays, Nano Lett. 14 (1), 346 (2014)

9161-8, Session 2

Facile synthesis of Cu_2S nanoarchitectures in application of surface enhanced Raman scattering

Shih-Yu Fu, Hao-Syuan Jhang, Yu-Kuei Hsu, National Dong Hwa Univ. (Taiwan); Yan-Gu Lin, National Synchrotron Radiation Research Ctr. (Taiwan)

Surface plasmon resonance (SPR) is one of the main mechanisms of surface Raman enhance scattering (SERS) and it will depend on the morphology and free carrier density of substrates, in many of discussions have been proved. Recently, the semiconductor copper(I) sulphide (Cu_2S), the natural p-type semiconductor, exhibits remarkable SPR in the near-infrared region and can be regards as best candidate for active SERS substrates. In this report, the successive ionic layer absorbance and reaction (SILAR) process will be used to synthesis Cu_2S nanotubes from ZnO nanorods as template deposited by electrochemical reaction. To further manipulate the different carrier densities of Cu_2S nanotubes, the adjustment of Cu vacancy in Cu_2S can be accomplished by exposure under oxygen ambiance. Taking 4-aminothiophenol (4-ATP) as probe molecule to measure the SERS performance by Cu_2S nanotubes made in this fabrication and also examines the effect on SERS by changing Cu vacancy under an exciting wavelength of 632.8 nm and light power of 15 mW. In fact, the modulation of Cu vacancy will positively correlate to the SPR frequencies and so could get the best enhancement factor under the limited condition of exciting source. Therefore, our results could provide a new opportunity to use SERS to explore the molecule-semiconductor interaction, a fundamental but essential question for designing novel devices.

9161-9, Session 2

Plasmon-enhanced optical properties of Au/TiO_2 core-shell nanowires studied by finite difference time domain calculation

Jubok Lee, Sun-Hee Lee, Min Su Kim, Hyungjung Shin, Jeongyong Kim, Sungkyunkwan Univ. (Korea, Republic of)

Recently various kinds of TiO_2 nanostructures hybridized with metal nanomaterials have been designed and shown to increase the power conversion efficiency and photocatalytic reaction by the enhancement of charge separation and broadening the spectral response into the visible wavelength regime. In this study, we fabricated the Au/TiO_2 core shell nanowires (NWs) and investigated optical properties of them such a photoluminescence (PL), Raman, and dark field scattering spectra in single NW level using high resolution laser confocal microscope. The results showed that PL of hybrid structures were greatly quenched due to the efficient charge separation occurring on the Au interface of hybrid structures. On the contrary, the scattering efficiency increased up to 3 times over plain TiO_2 nanowires by having hybrid structures with Au nano core and/or Au nanoparticles. The results were consistent with FDTD calculation that showed the increase of light scattering and field intensity on Au/TiO_2 core shell NW in the total magnitude and the spectral coverage. The actual photocatalytic efficiency of Au/TiO_2 NW was also measured to be superior to that of the plain TiO_2 NWs

9161-10, Session 2

Self-assembled nanoplasmonic structures with symmetry-breaking

Sui Yang, Xiaobo Yin, Boubacar Kante, Peng Zhang, Jia Zhu, Yuan Wang, Xiang Zhang, Univ. of California, Berkeley (United States)

The ability to light-matter interactions has been the driving force for the recent advancement of plasmonic materials whose subwavelength spatial structure and symmetry design enables unprecedented optical properties with possible applications ranging from sensing to imaging and information technology. Plasmonic structures with designed symmetries that can be realized by using traditional top-down approaches such as e-beam lithography only lead to strongly anisotropic and small-scale materials. In contrast, bottom-up approaches based self-assembly may offer advantages of large scalability and cost effectiveness, but often result in simple structures with high degree of symmetry because of the fact that complex and symmetry-breaking structures are often not thermodynamically favorable. A key challenge is how to overcome this limitation to build nanoplasmonic structures with broken symmetries that are essential to materials properties. Here we propose and experimentally demonstrate a novel plasmon guided self-assembly route to scalable synthesize this new class of symmetry-breaking nanoplasmonic strucutres with selectable optical magnetism. Through the study of symmetric effects of nanocomposites together with judicious nanoscale chemical binding control, we achieved symmetry breaking assemblies of two side-by-side gold nanorod dimer with a longitudinal offset, which defines the degree of symmetry-breaking that gives rise of intriguing optical modes. More importantly, we use structure-dependent plasmonic properties of gold nanodimers as their own structure guide to reshape the magnitude of symmetry interplays and structure homogeneity that led to realization of desired magnetic resonances. In conclusion, our research provides a novel optically selective self-assembly route to engineer symmetry-breaking nanophotonic materials with unique functionalities.

9161-11, Session 3

Hybrid materials: a bottom-up approach for nanotechnology applications *(Invited Paper)*

Giovanna Brusatin, Univ. degli Studi di Padova (Italy)

Engineered organic-inorganic hybrid materials, HyMat, offer new opportunities for the easy, fast and cheap development of optical devices. Integration of inorganic networks, organic functional groups and optically active molecules or nanoparticles allows to obtain combinations of properties and structures otherwise impossible with traditional material.

In particular, a simple and highly versatile synthesis platform is presented enabling preparation of HyMat, built up by a bottom-up sol-gel approach at low process temperatures. A few types of key building blocks constitute the way for accessing HyMat and make up their formulation, providing a means to synthetize innovative materials enabling to get:

- Optical active micro and nanostructures
- Miniaturized sensors for analytes in gaseous or liquid media
- Direct patternability with a range of lithographic techniques
- Variable inorganic and organic compositions and controlled porosity

Examples of micro and nano structures based on these spin-on materials with ceramic (i.e. GeO_2, TiO_2, ZrO_2, HfO_2, Al_2O_3) or silica based hybrid compositions will be presented for different applications including plasmonic or fluorescent sensors, high refractive index, etching masks, bio functionalization.

9161-12, Session 3

Enhanced stimulated emission in ZnO thin films using microdisk top-down structuring

Komla Nomenyo, Univ. de Technologie Troyes (France); Abde-Sattar Gadallah, Univ. de Technologie de Troyes (France) and Cairo Univ. (Egypt); Sergei Kostcheev, Univ. de Technologie Troyes (France); Dave J. Rogers, Nanovation (France); Gilles Lerondel, Univ. de Technologie Troyes (France)

Despite the absence of an effective p-ZnO junction and although ultraviolet lasers and LEDs based on GaN are readily available, ZnO is still interesting due to its large exciton binding energy, efficient radiative recombination and simpler crystal-growth processes which are significant for lower costs ZnO-based devices. On the other hand, ZnO structuring in order to realize photonic structures, has proved to be a critical issue that is faced up by the strong mechanical properties of ZnO, making of lithography one of the main challenges to confront for the fabrication of efficient ZnO lasers and LEDs.

In this work, ZnO microdisks were fabricated in planar thin film using a top-down approach combining electron beam lithography and reactive ion etching. These microdisk structured thin film exhibit a stimulated surface emission between 7 to 3 times higher than the reference film depending on the excitation power density. Narrowing, reduction in lasing threshold and blue shifting of the emission wavelength were observed along with the enhancement in the emitted intensity. Results clearly demonstrate that the light enhancement comes from the increase of the thin film internal quantum efficiency and the amplification of the stimulated emission. An analysis in terms of waveguiding is presented in order to explain these effects. These results are of great interest demonstrating that significant gain can be obtained using microstructured thin film which remains easier to fabricate than nanostructured ones.

9161-13, Session 3

Synthesis of high purity metal oxide nanoparticles for optical applications

Colin Baker, Woohong R. Kim, E. Joseph Friebele, Guillermo Villalobos, Jesse Frantz, L. Brandon Shaw, Bryan Sadowski, Jas S. Sanghera, U.S. Naval Research Lab. (United States)

In this paper we present our recent research results in synthesizing metal oxide nanoparticles for use as laser gain media and transparent ceramic windows via two separate techniques, co-precipitation and flame spray pyrolysis. The synthesis of high purity rare earth doped sesquioxide nanoparticles by a co-precipitation technique was performed by using highly purified nitrates of corresponding oxides. The nanoparticles were pressed into ceramic discs that exhibited superior optical properties. These transparent ceramics typically exhibited optical transmission approaching the theoretical limit and showed very high optical-to-optical lasing slope efficiency.

We have also synthesized sexquioxide nanoparticles using a Flame Spray Pyrolysis (FSP) technique. We present data demonstrating that the FSP system can be used to control the material phase of the nanoparticles, leading to the synthesis of a metastable phase of sesquioxide which has never been reported using this technique. Significantly, the presence of the metastable phase enables the ceramic powders to be hot pressed at lower temperatures resulting in excellent optical quality transparent windows with very fine grain sizes.

Finally, we present our research in the synthesis of rare earth doped Boehmite nanoparticles by Co-precipitation. The nanoparticles structure is chemically engineered so that the rare-earth ion is encased in a cage of Boehmite to prevent ion-ion proximity and energy transfer and they serve as precursors for fabricating high power fiber lasers. The nanoparticles are synthesized using precise pH control and ligand stabilization, allowing them to be doped into optical fiber preforms. The preforms have been drawn into fibers exhibiting long lifetimes and high laser efficiencies.

9161-14, Session 3

Ultrafast dynamics of coherent exciton-polaritons in ZnO/ZnMgO multiple quantum wells

Minfeng Chen, Academia Sinica (Taiwan); Yia-Chung Chang, Academia Sinica (Taiwan) and National Chiao Tung Univ. (Taiwan); Ja-Hon Lin, Yi-Kai Shen, Hsuan-Ching Lin, National Taipei Univ. of Technology (Taiwan); Wei-Ren Liu, Chia-Hung Hsu, National Synchrotron Radiation Research Ctr. (Taiwan); Chin-Chia Kuo, Wen-Feng Hsieh, National Chiao Tung Univ. (Taiwan)

We found striking time-dependent behavior of the carrier-induced change in transmission coefficient ($\Delta T/T$) through ZnO/ZnMgO multiple quantum wells (QWs) observed by femto-second pump-and-probe experiment. Instead of single (electron-hole plasma) EHP excitation (which decays exponentially) for bulk ZnO material as reported in the literature, multiple transient peaks of $\Delta T/T$ were observed and their behavior can be explained by the dynamic behavior of coherent exciton-polaritions in ZnMgO and their decay into electro-hole pairs in ZnO QWs.

A theoretical framework to investigate the ultrafast dynamics of coherent exciton-polaritons in ZnO/ZnMgO is developed. The Maxwell's equations coupled with polarization fields associated with excitons are used to model the dynamics of coherent exciton-polaritons. The following mechanism is proposed: 1) the first steep rise in (transient differential transmittance) TDT is attributed to the occupation of photo-excited EHPs in ZnO QWs that quenches the absorption of the probe beam by the (band filling) BF effect. After elapsing of the pump pulse, the non-radiative decay of EHPs weakens the BF effect that causes the exponential decay. The revivals of TDT evidence refueling of EHPs by coherent exciton-polaritons stored in barrier regions. The barrier polaritons could scatter into well EHPs while they tunnel through the ZnO QWs that were then observed by the probe pulse.

Based on the finite-difference time-domain modeling with physical phenomenological parameters, the subtle underlying physics is captured and we obtained good explanation of the experimental results, which illustrates a mechanism to monitor the dynamic behavior ofexciton-polaritons in ZnMgO.

9161-15, Session 3

Effect of annealing on the structural and optical properties of ZnO and AZO films prepared by sol-gel spin coating method

Sanjeev Kumar, Anil Kumar, Univ. of Delhi South Campus (India); Poonam Shokeen, Department of Electronic Science, University of Delhi South Campus, New Delhi - 110021 (India); Udaibir Singh, Univ. of Delhi (India); Fouran Singh, Inter Univ. Accelerator Ctr. (India); Avinashi Kapoor, Univ. of Delhi (India)

Zinc oxide (ZnO) and aluminum doped ZnO (AZO) thin films were fabricated on glass substrate by low cost sol–gel spin coating technique. ZnO thin films have the potential in the emerging thin-film technologies, which can be employed in thin-film solar cells, transistors, sensors and other optoelectronic devices. The influences of annealing temperature on the structural and optical properties of ZnO and AZO thin films were investigated. The structural properties of the ZnO films such as surface morphology and crystallinity were determined using atomic force microscopy (AFM) and X-ray diffraction (XRD), respectively. Our result shows an increase in the grain size and RMS surface roughness of the films with increasing annealing temperature from 200°C to 400°C. The optical properties of the ZnO films were characterized by the ultraviolet–visible (UV–vis) spectroscopy and Tauc method was adopted to explore the optical band gap. We get the optical band gap of ZnO films ranges from 3.26±0.01 eV to 3.34±0.01 eV and AZO films ranges from 3.28±0.01 eV to 3.32±0.01 eV. These values were very close to the band gap of intrinsic ZnO which is 3.37 eV. The reduction of the optical band gap with increasing annealing temperature can be due to the improved crystallinity and decreased defects of the films with higher annealing temperature. ZnO thin film with optical transmittance more than 90% was obtained with annealing temperature of 400°C. This could be the optimum annealing temperature for ZnO and AZO thin films to be employed in transparent conductive oxide (TCO) applications on glass and plastic substrates

9161-16, Session 4

Monitoring interfacial charge dynamics via FSRS *(Invited Paper)*

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Most of the efficiency losses in organic photovoltaic (OPV) systems result from charge carrier recombination which pre- vents charges from being transported to and collected by the electrodes. Recombination in these complex mesoscopic systems is poorly understood, thus making the engineering of materials with low recombination rates, and therefore high efficiency, very difficult. Additionally, OPV systems are distinct from traditional semiconductor PVs because of their molecular nature; in these systems molecular motions become extremely important

This project is aimed at gaining a more complete understanding of the vibrational motions that facilitate charge separation and transport within bulk heterojunction OPVs as well as the structural responses that occur during exciton migration, charge separation and charge transport. This knowledge will allow for intelligent design of chemical (i.e. structural) modifications of existing OPV materials, or synthesis of new ones, that will have lower charge carrier recombination rates leading to higher efficiency solar energy devices.

9161-17, Session 4

Highly crystalline urchin-like ordered arrays of ultra-thin zinc oxide nanowires: towards solar cell fabrication

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Well-ordered periodic arrangement of nanostructures with controllable enhanced surface morphology and advanced Light-matter Interaction control i.e. absorption and emission enhancement has recently become extremely relevant in terms of application. Flower or sea-urchin like ZnO nanostructures, grown by low temperature chemical processes on periodic 2D or 3D templates are one of the best candidates. The aim of this work is to demonstrate selective, patterned growth of ZnO using low cost, easy-to-fabricate templates by the bottom-up approach. This approach combines the fabrication of self-organized templates of functionalized polystyrene (PS) beads or silica beads followed by the growth of ZnO using low temperature chemical bath deposition method. ZnO nucleation layer is deposited on the PS beads prior to the synthesis of ZnO NWs. Formation of highly crystalline, luminescent ultra narrow NWs with diameter lower than 10 nm are observed to be formed around the PS beads leading to a new kind of urchin-like ZnO. The structural and optical properties of these urchin-like structures will be presented. These urchin-like ZnO structures have been successfully integrated as photoanodes in dye sensitized solar cells. Preliminary results will be discussed.

9161-18, Session 4

Nanocavity enhanced absorption of ultra-thin films

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In most thin-film energy harvesting/conversion applications, there is a long-existing trade-off between optical absorption and thickness of semiconductor materials. For instance, ultrathin-film photovoltaic devices and photocatalysis platforms may lead to the enhanced carrier extraction/transportation but insufficient light absorption. Particularly, when the absorptive materials are scaled down to atomically thin dimensions, their light-matter interactions are inherently weak. Consequently, absorption enhancement strategies will introduce revolutionary advances to these ultra-thin-film materials/devices. Here we propose a design by placing a predesigned lossless spacer layer between an ultra-thin absorptive material and a metal reflector to realize

spectrally tunable resonances absorbed in the top ultra-thin layer. As the incident light is coupled into this structure, the reflected components will cancel the incident light at the top surface, resulting in a destructive interference absorber. Since the bottom metal reflector does not absorb much light, most energy will dissipate in the top ultra-thin layer resulting in the significant absorption enhancement. By tuning the thickness of the spacer layer, the destructive interference resonance is spectrally tunable for ultra-thin absorptive materials down to atomic thickness, and therefore overcoming the conflict between the optical absorption and film thickness. This principle exploits the wave property of light and will pave the way towards the spectrally tunable absorption enhancement of ultra-thin materials.

9161-19, Session 4

Aluminum and copper plasmonics for enhancing internal quantum efficiency of core-shell and core-multishell nanowire photoelectrodes

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One of the most critical challenges for achieving solar-to-hydrogen (STH) efficiency greater than 10% (100 W/m2), especially in metal oxide photoelectrodes, is the poor internal quantum efficiency (IQE) arising from high, bulk and surface, recombination and insufficient light absorption. For instance, the theoretical STH efficiency of hematite photoelectrodes is about 15.5%, but the best studies employing various strategies such as nanowire geometry, doping, co-catalyst, surface state passivation, ‘dual absorber’ systems and plasmonic nanostructures demonstrated limited efficiencies between 5-6%. Plasmonics for light trapping particularly has emerged as a promising strategy to address this challenge. However, most designs are photocatalyst specific and employ precious metals, making large scale applications infeasible.

To address these challenges, we present metal-photocatalyst core-shell and semiconductor-metal-photocatalyst core-multishell nanowires as a novel class of multi-functional plasmonic photoelectrodes. Specifically, we explore aluminum and copper as plasmonic materials to ensure scalability of the photoelectrodes. We theoretically demonstrate that the size dependant localized plasmon resonances in such nanowires can be tuned to enhance absorption within ultrathin photocatalyst layers irrespective of the photocatalyst material choice. Such enhanced absorption ensures the photo-charges are preferentially generated very close to the photocatalyst-electrolyte interface and can effectively drive the reaction forward, thereby improving the IQE. We show that the absorption predicted in core-multishell nanowires employing aluminum come remarkably close to that of silver based core-multishell nanowires. Finally, we validate the generality of this approach by demonstrating absorption enhancement in nanowires with, and not limited to, Fe_2O_3, Cu_2O, CoO, WS_2 and MoS_2 as the photocatalyst.

9161-20, Session 4

Mixed ZnO nanoparticles as buffer layers of organic solar cells

Young-Kuk Kim, Kyu-Chae Choi, Youn-Kyung Baek, Eun-Jin Lee, Korea Institute of Materials Science (Korea, Republic of)

We demonstrate that mixture of nanoparticles of ZnO having different shapes can improve the photovoltaic performance of the inverted organic solar cells (IOSC) having blend of poly(3-hexylthiophene) and Phenyl-C61-butyric acid methyl ester as their active layer. In this study, we have synthesized ZnO spherical nanodots (NDs) and nanorods (NRs) from zinc acetate dihydrate (ZnOAc) with addition of strong bases dissolved in methanol and Transparent colloidal solutions having uniformly dispersed ZnO NDs or NRs were prepared by controlling solvent composition. Application of ZnO NRs as electron transporting layers for IOSC improved its short circuit current density (Jsc) compared with ZnO NDs-based buffer layers resulted from modification of energy barriers between electrode and active layers. However, insufficient surface coverage of ZnO NRs owing to agglomeration lowered fill factor and open circuit voltage (Voc) of the solar cell. Then, mixed buffer layers containing both ZnO NDs and ZnO NRs were applied and resulted in highly enhanced PCEs up to 4.12% due to improvement in Jsc by ZnO NRs and conservation of good surface coverage by ZnO NDs.

9161-32, Session PWed

Impact of hydrogen bonding in solvent for dispersion of ZnO nanocrystals on photovoltaic properties of organic solar cells

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We demonstrate that the morphology of ZnO buffer layers for the inverted organic solar cells (IOSC) was improved by controlling the molecular interaction in solvents to disperse of ZnO nanoparticles (NPs). Dispersion of ZnO NPs in non-polar solvent usually resulted in turbid or semi-transparent solution. In this study, uniform dispersion of ZnO NPs were achieved through applying mixed solvents composed of both non-polar and polar solvents without assistance of organic surfactant. From the analysis based on Hansen solubility parameter theory, this improvement was mainly associated with hydrogen bonding interactions between the two components of solvents. Smooth ZnO buffer layers were deposited using the colloidal solution based on the binary solvent mixture and the photovoltaic performance of the IOSC was highly improved by optimizing solvent mixtures.

9161-34, Session PWed

Highly transparent and conducting graphene embedded ZnO films with enhanced photoluminescence fabricated by aerosol synthesis

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Recently, mechanically exfoliated single-layer graphene sheets, transferred on top of ZnO film without chemical bonding, was reported to enhance ultraviolet photoluminescence (PL) of the ZnO due to a resonant excitation of a graphene plasmon. Low resistance and transparency are also crucial for improving the current injection and light extraction efficiency for the realization of solid-state lighting using LEDs. For these reasons, in the present work, we attempted to fabricate a transparent, conducting, and luminescent ZnO/graphene hybrid thin film using surface plasmon (SP) mediated photoluminescence.

For the hybridization of ZnO with graphene, an aerosol synthetic method: ultrasonic-assisted spray pyrolysis (UASP), was applied. One of the advantages of UASP is that multiple components can be incorporated into an aerosol droplet to serve different purposes. By adding additional components to the starting graphene precursor, inorganic particles wrapped by graphene nanoplatelets can be obtained. This aerosol synthetic route allows us to have a continuous mode of operation and readily scalable synthesis of large-area graphene-embedded thin film, or nano-composite particles.

The resulting ZnO/graphene thin film exhibits enhanced PL approximately three times greater than bare ZnO film. We have also shown that such PL enhancement can be achieved in a quasi-core-shell-type ZnO/graphene composite with reduced graphene oxide exhibits a larger PL enhancement than conventional reduced graphene oxide. Moreover, high optical transmittance (>80%) and increased electrical conductivity (>2 orders of magnitude) of the ZnO/graphene composite films show that the present composites are promising as transparent, conducting, and luminescent materials for use in optoelectronic devices.

9161-35, Session PWed

Coatable chromonic liquid crystal polarizer

Yu-Jin Choi, Dae-Yoon Kim, Pureun Im, Won-Jin Yoon, Ji-Tae Kim, Hui-Su Kim, Kwang-Un Jeong, Chonbuk National Univ. (Korea, Republic of)

A chromonic liquid crystal (CLC) polarizer was fabricated from Sunset Yellow FCF (H-SY) Macroscopic molecular orientation was achieved by bar-coating the self-assembled lyotropic CLCs and the oriented structure was frozen by the subsequent photo-polymerizing processes. Their molecular packing structures and optical behaviors were further investigated using the combined techniques of microscopy, scattering and spectroscopy. The polymer-stabilized H-SY films showed good mechanical and chemical stabilities without sacrificing a high polarizability. Therefore it can allow us to develop the smart optical and electrical devices. This work was mainly supported by the Human Resource Training Project for Regional Innovation, Converging Research Center Program, Basic Science Research Program (2013R1A1A2007238), Global Ph.D Fellowship Program (2013H1A2A11033907), and BK21 PLUS Program, Korea.

9161-36, Session PWed

Fullerene patterns in the elastically anisotropic cholesteric liquid crystals

Won-Jin Yoon, Pureun Im, Dong-Gue Kang, Yu-Jin Choi, Ji-Tae Kim, Hui-Su Kim, Kwang-Un Jeong, Chonbuk National Univ. (Korea, Republic of)

Fullerene-based reactive molecule (C60RM) was newly designed and synthesized. Its chemical structure and phase behavior were investigated with spectroscopic, scattering and microscopic techniques. In addition, the self-assembled striped C60RM pattern was successfully fabricated via the one-dimensional pattern-forming state of an elastically anisotropic cholesteric LC medium. This work was mainly supported by the Human Resource Training Project for Regional Innovation, Converging Research Center Program (2013K000404), Basic Science Research Program (2013R1A1A2007238), and BK21 PLUS Program, Korea.

9161-37, Session PWed

Surface-induced phase transition behaviors of the rod-disc molecule

Won-Jin Yoon, Dae-Yoon Kim, Yu-Jin Choi, Sang-A Lee, Kwang-Un Jeong, Chonbuk National Univ. (Korea, Republic of)

Rod-disc liquid crystal (LC) molecule (RD12) was newly designed and synthesized for characterizing and understanding of surface-induced phase transition behaviors of RD12 by changing the surface chemistry and the physical interactions. Upon varying the width of the LC cells and changing their surface chemical and physical states, the phase transition behavior of RD12 was rapidly changed. The nematic phase of RD12 in the LC cell with a low cell gap and polyimide rubbed surface could be preserved and the crystallization of RD12 was thoroughly controlled. It was concluded on the systematic experimental investigations that the glassy nematic phase was formed because of the fact that the surface anchoring force is bigger than the crystallization force. This work was mainly supported by the Converging Research Center Program (2013K000404), Global Ph.D Fellowship program (2013H1A2A1033907), and BK21 PLUS Program, Korea.

9161-38, Session PWed

Reversible actuation of an azobenzene-based photochromic liquid crystalline polymer

Yu-Jin Choi, Dae-Yoon Kim, Won-Jin Yoon, Sang-A Lee, Kwang-Un Jeong, Chonbuk National Univ. (Korea, Republic of)

We have newly synthesized a novel photochromic polymer (PLCP) via the acrylic diene metathesis polymerization. From the combined the techniques of DSC, POM and 2D WAXD, it was realized that PLCP formed a nematic (N) LC ordered phase containing the cynclinically tilted SmC-type cybotactic clusters, in which molecular packing structure is related to the head-to-side connected PLCP chemical structure. Additionally, we demonstrated the rewritable micro-patterned PLCP film by using light and/or heat. Due to the wireless remote controllability of reversible actuating and patterning behaviors of PLCP, it can be applied as a key material in opto-electronic and bio-mimetic devices. This work was mainly supported by the Human Resource Training Project for Regional Innovation, Basic Science Research Program (2013R1A1A2007238), Global Ph.D Fellowship Program (2013H1A2A11033907), and BK21 PLUS Program, Korea.

9161-39, Session PWed

Synthesis and characterization of highly luminescent CuInS2/ZnS quantum dots for near-infrared bio-imaging

Hyung Seok Choi, Jae Chul Park, Youngsun Kim, Mi Hwa Oh, Duk Young Jeon, Yoon Sung Nam, KAIST (Korea, Republic of)

Near-infrared (NIR) luminescent quantum dots (QDs) have been intensively investigated for in vivo bio-imaging applications. In particular, CuInS2/ZnS core-shell QDs (CIS/ZnS QDs) have received much attention for bio-imaging because of their high absorption coefficient, photostability, possible emission in the NIR spectra, and a relatively low level of cytotoxicity compared to cadmium-based QDs. In this study, we report a new synthesis method to prepare highly luminescent, NIR-emitting CIS/ZnS QDs with a diameter of about 3 nm at various emission spectra from visible to NIR region (570-730 nm). A simple heating-up method is employed using 1-dodecanethiol as a multi-functional agent, i.e., as a reaction medium, a sulfur source, and a capping ligand. In addition, by utilizing off-stoichiometry effects, the emission spectrum is controlled as the Cu/In ratio of the CIS core changes from 1/4 to 2/1. The synthesized CIS/ZnS QDs with a Cu/In ratio of 1.8 show a high photoluminescence quantum yield (PLQY) up to about 60 % at a maximum emission wavelength of 726 nm. The CIS/ZnS QDs are encapsulated within poly(methyl methacrylate) (PMMA) microspheres and dispersed in an aqueous solution. In vivo feasibility tests for deep-tissue bio-imaging applications are performed by intramuscular injection of the QD-loaded PMMA microspheres into a mouse model. Our results demonstrate that highly luminescent, NIR-emitting CIS/ZnS QDs are very attractive materials for deep tissue bio-imaging applications. Further investigation on size control up to the excitonic Bohr diameter (about 8.2 nm) and characterization of defect structures is now under way to increase PLQY in the NIR window.

9161-40, Session PWed

Luminescence studies on solid and nanostructured SiO_2:Eu^{3+} spheres obtained by sol-gel route

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Rare earths in confined systems are studied because their possible imaging applications. In this work we studied the optical properties of Eu3+ inside nanoporous spheres. Their properties were compared with these from europium in solid SiO2 spheres prepared by sol-gel method. Nanoporus channels were produced by using a surfactant. The last one was removed by chemical procedure. Then, europium was incorporated into the channels. XRD reveals the hexagonal structure of the pores. That was confirmed by HRTEM that shows the channels, clearly. N2 adsorption- desorption isotherm Type IV, characteristic of mesoporous materials, was obtained by BET. The I(5D0→7F2)/I(5D0→7F1) asymmetry ratio from Eu3+ transitions was obtained by photoluminescence. It had a value of 2.65 in the solid spheres and 1.65 in the nanoporous ones. That means Eu3+ is in an asymmetric site in both systems, and asymmetry is bigger in the solid spheres. Because the differences, we can use this parameter to distinguish between both systems, easily. Photoluminescence lifetimes were obtained for the 5D0→7F2 emission. It was shorter in the solid spheres than in the nanoporous ones, confirming there is a more asymmetric site for the rare earth in the first case. IR spectra shows Eu3+ is not incorporated as part of the SiO2 network.

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9161-41, Session PWed

Type-I InAs quantum dots covered by GaAsSb strain reducing layer

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This work is focused on examining ultrafast photoluminescent properties of InAs quantum dots (QDs) grown on GaAs substrate and covered by GaAs1-xSbx strain reducing capping layer (SRL). The samples were prepared by Stranski-Krastanow growth method. The aim is to understand the processes occurring inside the QDs and wetting layer (WL) and how the SRL influences the energy levels inside the QDs. It was already proven that the SRL of this composition can decrease energies of transitions inside these QDs to the IR range, which makes these structures promising candidate for devices emitting near infrared radiation. It is possible to shift the luminescence wavelength towards 1.3 and even 1.55 µm, which are widely used in telecommunications.

Using upconversion method we measured luminescence dynamics of two samples with different concentration of Sb in the SRL with sub-picosecond time resolution. We investigated the effect of temperature, as well as the intensity and wavelength of the excitation pulse. We also compared the properties of the samples after excitation by λ=760 nm pulse and 850 nm pulse – the former one is energetically above the GaAs substrate band gap; in the second case we excited only the QDs and the WL. We consequently derived recombination and relaxation processes occurring inside InAs QDs and also proved that the transport of charge carriers from the substrate and from the WL into the QDs is efficient.

9161-42, Session PWed

Three-dimensional branched nanowire heterostructures as efficient light-extraction layer in light-emitting diodes

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We report a facile method to fabricate three-dimensional branched ZnO/MgO nanowire heterostructures and their application as the efficient light-extraction layer in light-emitting diodes. The branched MgO nanowires are produced on the hydrothermally-grown ZnO nanowires with a small tapering angle towards the tip (~ 6 o), by the oblique angle flux incidence of MgO. The structural evolution during the growth verified the formation of the MgO nanoscale islands with strong (111) preferred orientation on very thin (5~7 nm) MgO (110) layer. The MgO nanobranches, are then grown on the islands, are polycrystalline consisting of many grains oriented in specific directions of <200> and <220>, supported by the nucleation theory. The LEDs with the branched ZnO/MgO nanowire arrays show a remarkable enhancement in the light output power by 21 % compared with that of LEDs with pristine ZnO nanowires. Theoretical calculations using a finite-difference time-domain method reveal that the nanostructure is very effective in breaking the wave-guiding mode inside the ZnO nanowires, extracting more light especially in radial direction through the MgO nanobranches.

9161-43, Session PWed

Optical attenuation of plasmonic Au-PDMS nanocomposite thin-film devices

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Compact description of far-field optical interactions between plasmonic nanocomposites and adjacent media permits facile a priori design of devices for light manipulation. Limited tractability of nanoscale descriptions at device-architectures previously limited development of plasmonic devices. Optical interactions between nanocomposites and adjacent optical elements, a simple device, are describable using infinite linear algebraic sums. Influence of plasmonic absorption and non-linear phenomena on device performance are distinguishable from measured transmission, reflection, and attenuation (resonant and non-resonant losses) of nanocomposites featuring nanoparticles in multiple dimensions. Two- and three-dimensional distributions of gold nanoparticles supported by silica and poly(dimethylsiloxane) substrates, respectively, are considered. A unique ternary map of transmission, reflection, and attenuation correlates far-field optical behavior to nanoparticle density and opacity of the adjacent element. Intuitive, visual specification of nanoparticle density and adjacent media needed to obtain a desired optical behavior is possible using the ternary map. The compact model and ternary map provide useful tools for the design and integration of plasmonic nanocomposites into photonic devices for sustainable energy and biomedical applications.

9161-44, Session PWed

Optical properties of solutions and thin films of silver and gold nanoparticles with hyaluronic acid

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Silver and gold nanoparticles have recognized importance in laboratory settings for colorimetric detection of proteins and DNA because of their unique optical, electrical and photothermal properties. Currently such nanoparticles have wide applications in diagnostic and therapeutic area. The main purpose of the study was to investigate optical properties of solutions and thin films of silver and gold nanoparticles with hyaluronic acid and they change under influence of different chemicals and modification procedure. We explored physicochemical properties of nanoparticles with size from 1 to 100 nm with prospect of their use as signal enhancers, optical sensors and biomarkers. For this purpose we synthesized silver and gold nanoparticles with size from 1 to 100 nm. Hyaluronic acid was used as composite agent. Thin films of nanoparticles were done by evaporation method. Ultraviolet-visible spectroscopy we used for study of optical and physical properties of silver and gold nanoparticles at all stages of the experiment. All structural changes of nanoparticles under influence of different chemicals and modification procedure were controlled by scanning and transmission

electron microscopy. The results showed that solutions and think films of silver and gold nanoparticles with hyaluronan have strong optical properties. Furthermore different chemicals lead to structural changes of nanoparticles and modification of their optical properties. Therefore, the solutions and thin films of silver and gold nanoparticles with hyaluronan have distinctive optical and physicochemical properties and can be applied as signal enhancers, optical sensors and biomarkers.

9161-45, Session PWed

Fabrication of chromonic nanofiber embedding self-assembled discotic sunset-yellow FCF dyes

Dong-Gue Kang, Dae-Yoon Kim, Pureun Im, Won-Jin Yoon, Yu-Jin Choi, Ji-Tae Kim, Kwang-Un Jeong, Chonbuk National Univ. (Korea, Republic of)

Chromonic nanofibers with the self-assembled Sunset-Yellow FCF nanocolumns were fabricated by electrospinning method. Based on the thermal, microscopic and scattering experiments, it was verified that Sunset-Yellow FCF molecules formed a glassy columnar nematic (N) phase in the PVP/H-SSY nanofiber. When the PVP/H-SSY nanofiber was annealed above the Tg of PVP, the H-SSY nanocolumns further self-organized into three-dimensional ordered crystals. The uniaxially oriented nanofiber mats embedding assembled nanocolumns may open the new doors for the practical applications of the spun fibers in optical, electronic and optoelectronic devices. This work was mainly supported by the Human Resource Training Project for Regional Innovation, Basic science Research Program (2013R1A1A2007238), Global Ph.D Fellowship Program (2013H1A2A1033907), and BK21 PLUS Program, Korea.

9161-46, Session PWed

Synthesis and characterization of a tetrathiafulvalene-based polymer

Pureun Im, Dong-Gue Kang, Ji-Tae Kim, Min-Wook Park, Kwang-Un Jeong, Chonbuk National Univ. (Korea, Republic of)

A photovoltaic polymer (6TTF-polymer) containing tetrathiafulvalene (TTF) was newly designed and synthesized via condensation polymerization. Furthermore, 6TTF-polymer containing fullerene (C60) is also polymerized to obtain both electron donor and electron acceptor moieties in the polymer chain. Electron-rich TTF can act as an electron donor and electron-deficient C60 can work as an electron acceptor. The chemical structure of 6TTF-polymer was characterized by utilizing FT IR, proton and carbon NMR spectroscopes and its thermal behavior was monitored by DSC. Furthermore, optical and electrochemical properties of the 6TTF-Polymer was investigated by using cyclic voltammetry, photoluminescence, and UV-Vis. The highest occupied molecular orbital level (EHOMO = -4.79eV) and band-gap energy (Eg = 1.91 eV) of the 6TTF-polymer suggested that TTF-based polymer could act as a good electron donating material for the optoelectronic applications. This work was mainly supported by the Human Resource Training Project for Regional Innovation, Basic Science Research Program (2013R1A1A2007238), and Converging Research Center Program (2013K000404), and BK21 PLUS Program, Korea.

9161-47, Session PWed

Hierarchical structures from the asymmetric amphiphilic tetrathiafulvalene molecule

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A novel amphiphilic molecule (amph-7TTF14) containing tetrathiafulvalene (TTF) was newly designed and synthesized. From the 2D WAXD pattern of the oriented amph-7TTF14 film, the crystal structure was identified to be a monoclinic unit cell. The main driving forces for the self-assembly of amph-7TTF14 were the face-to-face pi stacking interaction between TTF groups and the nanophase separation between rigid TTF groups and flexible hydrophobic alkyl and hydrophilic tri(ethylene oxide) tails. The morphological structure observed by using TEM, AFM, and POM indicated that the amph-7TTF14 formed not only flat ribbons but also scrolls and helixes. Based on the experimental results, it was realized that the scrolls and helices were induced by the unbalanced surface stresses generated during the crystallization process. This work was mainly supported by the Human Resource Training Project for Regional Innovation, Basic Science Research Program (2013R1A1A2007238), and Converging Research Center Program (2013K000404), Global Ph.D Fellowship Program (2013H1A2A1033907), and BK21 PLUS Program, Korea.

9161-48, Session PWed

Characteristics of YAG-doped ZnO/ITO deposited by spraying methed

Wun Wei Lin, National Taipei Univ. of Technology (Taiwan)

This study presents a novel white light device consisted of a yttrium aluminum garnet (YAG) phosphor-doped zinc oxide (ZnO) (ZnO:YAG) thin film deposited on a indium tin oxide (ITO) glass substrate by ultrasonic spray pyrolysis(USP).

Growth of YAG phosphor-doped zinc oxide (ZnO) film was deposited by an USP method on ITO substrates. First step the ZnO:YAG film samples at 500°C and atmospheric pressure in nitrogen (N2) gas flow fixed rate of 100 sccm for one hour. Second step the samples at 400°C in air for 10 min. Characteristics of the ZnO:YAG film on ITO glass substrates. The ZnO solution sources of Zn(CH3COO)2•2H2O (0.5 M) and CH3COONH4•2H2O (0.5 M) with 1:3 proportional ratio, and the phosphor powder (NYAG4156 phosphor, INTEMATIX) was added into the ZnO solution source solution to form the spraying aqueous solution. The YAG phosphor at 0, 1, 5 and 10 wt.%. were examined by x-ray diffraction (XRD) pattern, hall measurement, and photoluminescence (PL) pattern spectra. The color of the PL spectra of the yttrium-aluminum garnet (YAG) phosphor-doped zinc oxide (ZnO) thin films under excitation of He-Cd laser with wavelength of 325 nm is nearly white.

9161-49, Session PWed

Nonlinear properties of IGZO thin films prepared by RF magnetron sputtering

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ABSTRACT

Transparent conducting indiuim galium zinc oxide (IGZO) films were successfully grown on glass substrates at room temperature by RF magnetron sputtering. Structural, optical, morphological and electrical properties of IGZO films deposited at different RF power were investigated. Composition of the film was analysed by EDAX measurement which shows that percentage of Zn increased with the RF power. Surface morphology of the IGZO film measured from AFM analysis showed that the roughness of the film was increased with increase in RF power. The average transmission in the visible range was greater than 80% and the transmission in the higher wavelength region decreased with increase in RF power. The carrier concentration in IGZO films could be controlled by controlling RF power due to the increase of Zn/(Ga+In+Zn) ratio. Nonlinear properties of IGZO thin films were measured using z-scan technique. Increase in free electron co concentration of IGZO thin films lead to a decrease of the corresponding nonlinear optical absorption response.

9161-21, Session 5

Metal oxide and metal-metal oxide hybrid nanostructures for applications of catalysis and smart windows *(Invited Paper)*

Taleb Mokari, Ben-Gurion Univ. of the Negev (Israel)

No Abstract Available

9161-22, Session 5

Sensors based on facet dielectric metamaterial

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The sensors for the detecting and analyzing bio and chemical substances is the important application for the modern metamaterials. We suggest the new dielectric metamaterial with facet structure, where the local electromagnetic field is much enhanced in comparison with the amplitude of the incident light. Each facet operates as a micro resonator of Fabry-Perot type. The incident light excites these micro resonators that have various resonance frequencies. The em field oscillations in the facets interact and form the collective modes that are spatially localized in hot spots, where local field has maxima. The incident light pumps energy in the localized modes increasing to giant values the local em field. The planar metamaterial with facet structure were prepared by electron-beam deposition of the cerium dioxide on the special alumina ceramics. The internal stress accumulates in the process of the deposition. We found the parameters of the deposition process when the relaxation of the stress results in the formation the facet structure. The elementary cell of the facet structure has hexagonal shape and it is separated from the other facets by the nano-gaps which thickness is much less than the average size ~ 3 mic of the facets. To detect the field enhancement we deposit the gold nanoparticles on the surface of the metamaterial. The surface concentration was about few particles per one cell. The organic acid known as DTNB was adsorbed on the surface of the gold particles. The giant enhancement of the Raman signal from DTNB is detected.

9161-23, Session 5

High temperature ceramics based nanophotonic structures

Manfred Eich, Technische Univ. Hamburg-Harburg (Germany)

The talk will present our research on novel high temperature hierarchical nanomaterials concepts which are a focus of our collaborative research program on taylor made multiscale materials systems. We will report on titania and zirkonia based ordered and also disordered 3D structures which are designed and fabricated in order to very effectively reflect heat radiation in high temperature environments (T>1000 degC). The theoretical and experimental photonic properties and the fabrication details and thermal properties of thin layers of such 3D structures will be discussed. Due to their porosity these structures also employ a very small thermal conduction and thus can replace conventional thermal barrier coatings in air craft and power generation gas turbines. In addition, the presentation will cover high temperature stable structures that can be designed to show narrow band thermal far field emission properties as well as can enhance near field thermal transport via their hyberbolic optical properties.

9161-24, Session 5

Direct printing of planar photonic circuits with high refractive index

Carlos A. Pina-Hernandez, abeam Technologies, Inc. (United States); Aleksandr Polyakov, Lucas Digianantonio, The Molecular Foundry (United States); Giuseppe Calafiore, Sergey Babin, abeam Technologies, Inc. (United States); Stefano Cabrini, The Molecular Foundry (United States); Christophe Peroz, abeam Technologies, Inc. (United States); Alexander Koshelev, Alexey Bugrov, Alexander Goltsov, Nano-Optic Devices (United States)

The nanopatterning of high refractive index optical films promises the development of novel photonic nanodevices such as optical integrated circuits or imaging sensors. As a first step, we report here for the first time a printable photonic circuit fabricated by direct imprinting of inorganic films with high refractive index.

Hybrid organic/inorganic printable materials based on TiO_2 were developed for crack free films with high transparency. Printed nanophotonic devices with sub-10 nm resolution were achieved in a single UV-imprinting step by applying low pressure (<3 bar) [1]. The imprinting was performed with flexible PDMS and hard Ormostamp templates. The patterned films were annealed at high temperatures to transform the hybrid material into inorganic TiO_2 with high refractive index. The optical properties of the fabricated nanostructures can be easily tuned by controlling the post-annealing conditions; for instance, a refractive index higher than 2.0 and an extinction coefficient close to zero can be achieved in the visible wavelength range. We will present and discuss material characterization as well as the optical properties of the first printable planar optical circuits. The printed circuit is composed of curved multi-mode ridge waveguides (RWG), wavelength demultiplexers based on digital planar holograms (DPH) and directional light couplers.

Our technology opens an original route for fabricating novel printable photonic devices at low cost and high throughput.

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9161-25, Session 5

Block copolymer assisted refractive index engineering of metal oxides for applications in optical sensing

Zsolt L. Poole, Univ. of Pittsburgh (United States); Paul R. Ohodnicki Jr., National Energy Technology Lab. (United States); Michael Buric, National Energy TEchnology Laboratory (United States); aidong yang, Univ of Pittsburgh (United States); Shaymaa Riyadh, Univ. of Bagdhad (Iraq); Yuankun Lin, Univ. of North Texas (United States); Kevin P. Chen, Univ. of Pittsburgh (United States)

We demonstrate in this paper that the refractive indices of important sensory metal oxides (TiO_2, SnO_2, ZnO, etc.) can be altered “at will” to meet the on-fiber refractive index compatibility requirements for optimal sensory integration. The tailoring of the refractive indices is accomplished by controlled 3D nanostructuring in the sub-100nm (sub-wavelength) domain using the method of block-copolymer templating combined with the sol-gel approach. Metal oxides are an important class of functional materials in chemical and biosensing due to the charge transfer interactions that take place at the surface with a chemisorbed species. The inert nature of silica, which at the same time permits its operation in a wide array of extreme conditions, limits its sensory capability. The integration of these highly developed sensory metal oxides with the optical fiber platform has seen limited success due to the large refractive index incompatibility (n_{silica} ~ 1.46, $n_{metal-oxide}$ > 2). Some thin film coatings have been shown to function but their functionality

has not been well developed and their sensory responses not well explored. Therefore, we present three novel advances in regards to the integration of functional metal oxides with the fiber platform. First, that the refractive indices can be tailored to meet the on-fiber compatibility requirements. Second, we demonstrate the type of the optical response by incorporating a high temperature stable fiber Bragg grating. And third, we present numerical modeling results that well describes the operation of metal oxide coatings, whether refractive index adjusted thick films or high refractive index thin films.

9161-26, Session 6

Polymer based nanocomposites with tailorable optical properties *(Invited Paper)*

Roberto Simonutti, Univ. degli Studi di Milano-Bicocca (Italy); Annalisa Colombo, Univ. degli Studi di Milano-Bicocca (Italy) and Fondazione CIFE (Italy)

A recurring challenge in the field of polymeric nanocomposites is the control of the spatial distribution of nanoparticles (NPs) in the polymer matrix. It is well-decreed that a specific NP dispersion state is necessary to obtain the desired property of polymer nanocomposites. In particular, there is considerable interest in dispersing luminescent or high refractive index NPs into transparent and uncolored polymer matrices, with the final goal of obtaining a solar concentrator or increasing the polymer's dielectric constant. Important for these materials is that scattering needs to be minimized, a requirement that is met by ensuring that the NPs are uniformly well-dispersed in the polymeric matrix. Different approaches have been developed in order to reduce the particle-particle attraction, that causes segregation between the inorganic and polymeric phases, like the brush-induced steric stabilization. In this case the surface of the NP is modified in such a way to be covered by a brush of organic molecules, the good dispersion conditions are to be find balancing the enthalpic and entropic terms of the interaction among the NPs surface brushes and the polymer chains. Two main applications will be described. The first is the fabrication and characterization of a luminescent solar concentrator based on giant CdSE/CdS quantum dots (QDs). It will be shown that the incorporation of the QDs in the polymer matrix does not cause any degradation of their emission efficiencies. Finally, polymer nanocomposites, based on acrylic polymers and TiO2 NPs, with refractive index as high as 1.89 will be presented.

9161-27, Session 6

Multi-physics modeling of photonic and excitonic properties of DNA-based nanostructures

Étienne Boulais, Massachusetts Institute of Technology (United States); Nicolas Sawaya, Harvard Univ. (United States); Keyao Pan, Massachusetts Institute of Technology (United States); Alán Aspuru-Guzik, Harvard Univ. (United States); Mark Bathe, Massachusetts Institute of Technology (United States)

Precise spatial organization of chromophores and inorganic materials at the nanometer-scale yields unique optical properties that are important to the discovery and development of novel photonic systems. In particular, natural photosynthetic apparatus present in bacteria provide inspiration for biomimetic nanoassemblies of dye molecules that may yield highly efficient synthetic light-harvesting complexes.

Programmed self-assembly of DNA uniquely enables the precise construction of such complex nanometer-scale architectures. The scaffolded DNA origami approach utilizes 'staple strands' of single-stranded DNA that hybridize to a complementary target 'scaffold strand' in solution to form megadalton-scale 3D molecular architectures. These assemblies act as molecular pegboards to assemble dye molecules with angstrom-level precision.

In this work we present a multi-physics computational procedure that enables exploring, designing and characterizing novel emergent photonic and excitonic properties of such scaffolded dye assemblies. Atomic-level solution DNA nanostructures are predicted using the finite element based framework CanDo (http://cando-dna-origami.org) that uses DNA sequence design to predict the 3D solution shape and mechanical properties of megadalton-scale DNA-based architectures. Atomic reconstruction of DNA assemblies with scaffolded dyes is subsequently generated as input to molecular dynamics simulation of DNA-dye complex conformational dynamics. Dye positions and orientations are used to compute energy transfer, using the Förster theory for dilute systems, and a hybrid classical/quantum approach for densely packed dye assemblies, when quantum coherence and excitonic coupling become significant. Quantitative prediction of experimental structures and optical properties of DNA-dye architectures verifies our approach. This framework promises to be of major importance for the discovery of next-generation DNA-based nanophotonic materials.

9161-28, Session 6

Spatially adjusted spontaneous emissions from photonic crystals embedded light-emitting diodes

Yu-Feng Yin, Yen-Chen Lin, National Taiwan Univ. (Taiwan); Yi-Chen Liu, Hai-Pang Chiang, National Taiwan Ocean Univ. (Taiwan); Jian-Jang Huang, National Taiwan Univ. (Taiwan)

In this work, the angular light output enhancement of LEDs was investigated from the spontaneous emission and light scattering of devices with different photonic crystal (PhC) geometries. The emitted photon coupled into a leaky mode is differentiated by the manipulation of quality factor in various spatial frequencies. Therefore, light extraction in this light-emitting device is determined by the modal extraction lengths and the quality factors obtained from the measured photonic bands. Furthermore, the higher- and lower-order mode spontaneous emissions are affected by the nonradiative process in the PhC structures with different lattice constants. In our cases, the photonic crystal device with the largest period of 500 nm exhibits the highest low-order mode extraction and quality factor. As a result, a self-collimation behavior toward the surface normal is demonstrated in the 3D far-field pattern of such a device. We conclude that, with the coherent light scattering from the PhC region, the spontaneous emission of the material and spatial behavior of the extracted mode can be both managed by the proper design of the device.

9161-29, Session 6

Ultrahigh-contrast and large-bandwidth thermal rectification in near-field electromagnetic thermal transfer between nanoparticles

Linxiao Zhu, Clayton R. Otey, Shanhui Fan, Stanford Univ. (United States)

We exploit the unique properties of optical waves in nanophotonic structures to enhance the capabilities for active control of electromagnetic thermal transfer at nanoscale. We show that the near-field electromagnetic thermal transfer between two nanospheres can exhibit a thermal rectification effect with very high contrast and large operating bandwidth. A thermal rectifier, is a two-body device that operates in a nonequilibrium condition so that for a given temperature bias, the magnitude of heat flow between the bodies depends on the direction of the temperature bias. In this work, we consider near-field electromagnetic thermal transfer between two nanospheres, made of same type of SiC. Since these spheres are much smaller than the free-space wavelength for the relevant resonance modes, it is known that their resonances are scale invariant, i.e., the resonance frequencies are independent of the radius of the sphere, whereas the spatial distribution of the resonance modal field scales directly with the radius of the sphere. We show that such a scale invariance property results in a significant asymmetry in the relevant coupling constants between the modes in the spheres, and hence provides a rectification mechanism that is distinctly different from all previous works. For a photon-based thermal rectifier, such a mechanism significantly enhances its performance. We also show that the three-dimensional nanoscale modal confinement in these systems directly enables high-speed operation of the device. Our work shows that the unique modal properties of nanophotonic structures can be exploited to create a powerful mechanism for achieving new thermal functionalities.

9161-30, Session 6

Heating processes in plasmonic resonances: a non-linear temperature dependent permittivity model

Alessandro Alabastri, Francesco De Angelis, Remo Proietti Zaccaria, Istituto Italiano di Tecnologia (Italy)

Heating processes in plasmonics are essential every time the interaction with electromagnetic fields induces dissipation within metallic nanostructures. In particular the capability to predict the final temperature reached by a system (e.g. an ensemble of nanoparticles within a host medium) can be crucial when dealing with electronic, medical or chemical applications. Here we present a dispersive model of the dielectric function of a metallic medium which depends on temperature. Since temperature, in turn, depends on the intensity of the electromagnetic source and on the optical response of the medium itself, the model expresses non-linearity features. The model, which does not require any fitting parameter, can be utilized whenever the impact of temperature on the optical response of a system needs to be clarified and/ or when non-linearities might play a major role.

9162-1, Session 1

Purcell factors and other interesting quantum optical effects with nanoplasmonic resonators *(Invited Paper)*

Stephen Hughes, Queen's Univ. (Canada)

No Abstract Available

9162-2, Session 1

Modal representation of light-matter interactions in plasmonic nanoresonators *(Invited Paper)*

Christophe Sauvan, Jean-Paul Hugonin, Philippe Lalanne, Institut d'Optique Graduate School (France)

We have developed a self-consistent electromagnetic theory of light-matter interactions in nanoresonators. The theory that relies on the concept of quasinormal modes with complex frequencies is capable of accurately handling any photonic or plasmonic resonator with strong radiation leakage, absorption and material dispersion. We use the modal formalism to revisit Purcell's factor. The new formula substantially differs from the usual one; in particular, we predict that a spectral detuning between the emitter and the resonance does not necessarily result in a Lorentzian response in the presence of dissipation. More generally, we derive a modal expansion of the imaginary part of the Green tensor. This modal representation provides a powerful tool to calculate and understand the degree of spatial coherence in complex photonic or plasmonic systems.

9162-3, Session 1

Interaction of a quantum emitter with a meta--surface

Didier Felbacq, Univ. Montpellier 2 (France)

Metasurfaces are the two-dimensional analogue of metamaterials. They are made of thin resonant structures deposited on a surface. They allow for the control of phase, wavefront, polarization or refracted energy of light. A metasurface made of ultrathin resonant wires was considered. Confined Bloch modes arise due to resonances and form a natural basis to characterize the spontaneous and stimulated decays of a quantum emitter placed near the surface.

The dispersion relation for the Bloch modes was obtained by of an asymptotic theory for each scatterer, coupled to a multiple scattering theroy.

Computing typical quantum properties such as the spontaneous or stimulated emission rates requires the knowledge of the density of electromagnetic states, a classical quantity. For the resonant metasurface under study, the crossed density of states of the system was calculated in terms of the continuum of scattering states as well as the Bloch modes. This requires a deformation of the integral over plane waves in the complex planes of wavevectors. This makes possible to specify a probability of de-excitation over the different open channels and the engeneering of the coupling over localized modes. In particular the various regimes of strong and weak coupling were investigated with the aim of studying the coupling of energy between localized Bloch modes and a quantum emitter.

9162-4, Session 1

Spontaneous emission dynamics of quantum emitters coupled to epsilon-near-zero metamaterials

Ruzan Sokhoyan, Georgia T. Papadakis, Ho Wai Lee, Harry A. Atwater Jr., California Institute of Technology (United States)

Coherently coupled quantum emitters are likely to constitute important elements of future quantum computing and communication systems. In free space, interactions between quantum emitters drastically diminish when the inter-emitter spacing is comparable to half a resonant wavelength. Coupling quantum emitters to an environment with carefully tailored local density of optical states (LDOS) could dramatically increase their interaction range. Within the framework of macroscopic quantum electrodynamics [1], we articulate here how coupling quantum dipole emitters to an epsilon-near-zero (ENZ) metamaterial enables the observation of quantum cooperative effects, focusing on the collective decay of emitters. In the present work, we consider ENZ metamaterials composed of multilayer metal-dielectric stacks, which have shown to exhibit ENZ behavior for a small range of wavelengths [2]. First we analyze the spontaneous emission enhancement of a dipole emitter for the cases when the emitter is in the proximity of the metamaterial or is embedded into the layered metamaterial structure, and we compare our results with those from the homogenized effective-medium approach [3]. Further, by scanning over different resonant frequencies of the quantum emitters, we investigate how inter-emitter interactions vary when approaching the ENZ regime of the metamaterial. We calculate the collective decay rate and the dipole-dipole coupling parameter as a function of positions and resonant frequencies of the emitters and investigate the superradiant behavior of quantum emitters in the ENZ regime.

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9162-5, Session 1

Advanced emission manipulation in quantum-dot metamaterials *(Invited Paper)*

Manuel Decker, Isabelle Staude, Sergey S. Kruk, Dragomir N. Neshev, Yuri S. Kivshar, The Australian National Univ. (Australia)

Plasmonic nanoparticles have proven to provide a very effective way to control and enhance the photoluminescence properties of quantum emitters due to their ability to confine light to ultra-small volumes and, therefore, have large potential for applications in the field of solar-energy harvesting, efficient photodetection, and biosensing [1,2]. Particularly more complex-shaped nanoparticles that can be incorporated as meta-atoms in metamaterials can be used to specifically tailor the spontaneous emission of semiconductor quantum dots (QDs) beyond the mere enhancement of the photoluminescence (PL) signal.

Here, we report on our experimental investigations to answer the question how the energy of QDs is distributed when several metamaterial modes of very different characteristics - like electric and magnetic metamaterial modes - are present [3]. By superimposing two orthogonal modes of equal strength at the wavelength of QD-PL, we demonstrate a sharp difference in their interaction with the magnetic and electric metamaterial modes. We also demonstrate that the polarization-state of emission is critically dependent on the multipolar properties of the metamaterial resonances. We propose the novel concept of manipulation of the polarization state of light emission in a system of QDs coupled to a multipolar resonance in metamaterials. In particular, we show that the superposition of several resonant multipolar contributions (e.g. electric/magnetic dipole moments, quadrupole moments etc.) leads to the emission of chiral light of opposite handedness.

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9162-6, Session 2

Fabrication of InGaN quantum dots for use as active photonic emitters *(Invited Paper)*

Arthur J. Fischer, Xiaoyin Xiao, Ganapathi S. Subramania, Jeffrey Y. Tsao, Daniel D. Koleske, Ping Lu, Jeremy B. Wright, Sheng Liu, George T. Wang, Sandia National Labs. (United States)

Fabricated quantum dots (QDs) are desired for a wide variety of applications including emitters for full-color compact projectors, optical data storage, solid state lighting, and single photon sources. InGaN QDs are particularly promising for solid state lighting applications where strain relaxation allows for more In incorporation and efficient emission at yellow and red wavelengths. InGaN material grown by metalorganic chemical vapor deposition is fabricated into QDs using post-growth etch processing. Atomic force microscope measurements show InGaN QDs in the size range from 2 to 10 nm with a density of ~10^11 dots/cm2. Transmission electron microscopy x-ray analysis shows clear evidence of InGaN QDs on the surface of the GaN template layer. Micro-photoluminescence measurements with 266 nm pumping and a 1 micron pump spot size show emission at ~420 nm. The InGaN photoluminescence peak shifts by ~20 nm showing that we can increase the quantum confinement via etch processing. InGaN material with a GaN capping layer also showed a 2 to 4 times increase in PL efficiency compared to uncapped InGaN material demonstrating the need for passivation of InGaN QDs. With further development work, the fabrication method used here to demonstrate InGaN QDs has the potential for demonstrating single QDs at deterministic locations inside photonic crystal structures. Sandia National Laboratories is a multiprogram laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04–94AL85000.

9162-7, Session 2

Physics of local quantum states in carbon nanotubes for photonic applications *(Invited Paper)*

Yuhei Miyauchi, Kazunari Matsuda, Kyoto Univ. (Japan)

Single-walled carbon nanotubes (SWNTs) are extremely thin cylinders of hexagonal carbon networks with diameters on the order of 1 nm, and can be metal or semiconductor depending on their chiral structure. Semiconducting SWNTs exhibit near infrared luminescence, and their emission wavelengths (~900-1600 nm for SWNTs with diameters of ~ 1 nm) are suitable for photonic applications in telecommunication and bio-imaging. Here we will review our recent studies on exciton physics of local quantum-dot-like states embedded in SWNTs. We will discuss the advantages and limitations of using SWNTs as near-infrared light emitters, and how the local states affect the optical properties of SWNTs. Then we will give an overview of the impacts and benefits of embedding the local quantum-dot-like states in quasi-one-dimensional SWNTs for their applications as near infrared light emitters. Especially, we have recently found a drastic enhancement of the luminescence quantum yield of excitons due to the dimensionality modification of excitons in the local states; the detailed mechanism of the enhancement will be discussed. We will also review our recent efforts towards understanding universal exciton dynamics in one-dimensional nanostructures with sparse zero-dimension-like states through nonlinear luminescence spectroscopy on the local states in SWNTs with different density and origins.

9162-8, Session 2

Yellow single-photon emission from nitrogen impurity centers in AlAs *(Invited Paper)*

Masafumi Jo, RIKEN (Japan) and National Institute for Materials Science (Japan); Takaaki Mano, Takashi Kuroda, Yoshiki Sakuma, Kazuaki Sakoda, National Institute for Materials Science (Japan)

Isolated impurity centers in semiconductors are attractive as quantum light sources because of their superior homogeneity and scalability. Nitrogen (N) has a large electronegativity and a small atomic radius compared with other V-column elements, and the substitutional N atoms in III-V formed isoelectronic impurity centers around the position where the excitons were localized. The aim of this study was to demonstrate the visible single-photon generation from N impurities in AlAs.

Nitrogen delta-doped AlAs was grown on a GaAs(001) substrate using a molecular beam epitaxy machine equipped with a radio-frequency nitrogen plasma source. Optical properties of the individual centers were investigated by steady-state and time-resolved photoluminescence. The electronic states for the N impurities in AlAs were calculated using the valence-force-field and tight-binding methods.

Sharp emission lines from excitons bound to the N impurities were observed at 2.1–2.2 eV, below the X conduction band minima in AlAs. The quadratic increase in the photoluminescence intensity with the N concentration indicated that the nitrogen impurity centers consisted of NN pairs. In contrast, the emission associated with isolated N impurities was not observed. The calculations showed that an isolated N atom formed a resonant state above the conduction band edge in AlAs. In contrast, NN1[110] and NN4[220] pairs formed bound states inside the band gap. Photon correlation measurement produced the second-order correlation function $g^{(2)}(0) = 0.33$. This demonstrates the generation of non-classical light in the yellow wavelength range from an NN pair in AlAs.

9162-9, Session 3

Realizing a quantum transistor using a quantum dot strongly coupled to a cavity *(Invited Paper)*

Edo Waks, Hyochul Kim, Ranojoy Bose, Tao Cai, Shuo Sun, Univ. of Maryland, College Park (United States); Glenn S. Solomon, National Institute of Standards and Technology (United States)

Two dimensional photonic crystals have been recognized as a highly promising device platform for compact integrated photonics. They can also localize and trap light to spatial volumes on the order of a cubic wavelength, resulting in large electromagnetic intensities. By embedding a single quantum dot (QD) in the high field region of photonic crystal cavities it becomes possible to achieve strong light-matter interactions at the single photon/single atom level. These unprecedented interaction strengths open up the possibility for creating nonlinear optical effects approaching the single photon level. In addition, they can be exploited to engineer unique quantum mechanically entangled states of light and matter that enable scalable quantum networks. In this talk, I will discuss our work on coupling indium arsenide (InAs) QDs to photonic crystal structures in order to realize a quantum transistor, where the quantum state of the dot conditionally rotates the state of an incident photon. This device applies a universal quantum CNOT gate to a photon, which is the basic building block for universal quantum computation. We demonstrate the coherence of the transistor via the observation of Rabi oscillations, which show that we are directly controlling the quantum state of the device. Our results provide a step towards scalable quantum networks and distributed quantum computers implemented in a compact nanophotonic device platform.

9162-10, Session 3

Large-alphabet quantum key distribution using time-energy entangled photons

Dirk R. Englund, Catherine Lee, Jacob Mower, Zheshen Zheng, Franco N. C. Wong, Jeffrey H. Shapiro, Massachusetts Institute of Technology (United States)

Quantum key distribution (QKD) enables two parties, Alice and Bob, to establish a private cryptographic key at a distance. Practically, the rate of key generation is limited by experimental constraints, such as the rate of generating photons or the repetition rate of single photon detectors. However, Alice and Bob can increase the amount of shared information per detected photon by using of high-dimensional photon correlations. Here, we will describe a QKD protocol that employs time-energy correlations between entangled photons[1,2]. The security analysis of this protocol relies on estimating the time-frequency covariance matrix of Alice's and Bob's measurements, which enables Alice and Bob to bound Eve's maximum obtainable information. We have implemented high-dimensional time-energy QKD protocols using commercially available telecom dispersion emulation systems, enabling high generation rate and photon information capacity in excess of 3 bits per detected photon coincidence.

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9162-11, Session 3

Generation of photon pairs with reconfigurable entanglement on a nonlinear chip *(Invited Paper)*

Andrey A. Sukhorukov, James G. Titchener, Che Wen Wu, Alexander S. Solntsev, Dragomir N. Neshev, The Australian National Univ. (Australia)

Integrated quantum optical circuits have the potential to produce and control entangled photons far more efficiently than traditional bulk optics. Spontaneous parametric down-conversion (SPDC) can provide an 'on-chip' source of entangled photons in structures with quadratic nonlinearity, so that there is no need to generate entanglement externally to the quantum circuit. Engineering the properties of the photonic structure can enable us to control the photon propagation within the integrated circuit.

We show that biphotons with any desired complex spatial entanglement can be generated in nonlinear waveguide arrays (WGA) with specially optimized characteristics. This photon source can be integrated on a chip for processing of the generated path-encoded qudits.

The propagation of biphotons in a waveguide array is governed by a linear Schrödinger-type equation, so driving all three waveguides simultaneously will produce a linear superposition of the output states that would be produced if the waveguides were driven individually. Hence altering the amplitude and phase of the driving lasers allows switching between the states spanned by the set of single waveguide outputs.

In order to manipulate the biphoton generation within the WGA, we engineer the sign of the effective quadratic susceptibility along the length of each waveguide. This can be achieved in practice by altering the domain structure through electric poling, representing a feasible route towards an 'on chip' reconfigurable source of spatially entangled photons.

We also show that by employing adiabatic waveguide coupling, we can generate spatially entangled photon pairs while simultaneously providing spatial pump filtering and keeping photon-pair states pure. We estimate the performance of the pump filtering to be of the order of 72 dB. Moreover the proposed method is highly tolerant to fabrication inaccuracies.

9162-12, Session 4

Quantum dots with engineered multi-carrier interactions for light-emitting diodes *(Invited Paper)*

Victor I. Klimov, Los Alamos National Lab. (United States)

Lighting consumes almost one-fifth of all electricity generated today. A dramatic improvement in lighting efficiency is possible by replacing traditional incandescent bulbs by light-emitting diodes (LEDs) in which current is directly converted into photons via the process of electroluminescence. The focus of this presentation is on the emerging technology of LEDs that use solution-processed semiconductor quantum dots (QDs) as light emitters. QDs are nanosized semiconductor particles whose emission color can be tuned by simply changing their dimensions. They feature near-unity emission quantum yields and narrow emission bands, which results in excellent color purity. These properties make QDs attractive for applications in lighting and display technologies. This presentation overviews spectroscopic studies of QDs that address the problem of nonradiative carrier losses in QD-LEDs, and approaches for its mitigation via the appropriate design of QD emitters. We consider processes such as carrier recombination via surface defects including hot-electron trapping, discussed in the context of QD emission intermittency ("blinking"). We also analyze nonradiative Auger recombination in the presence of extra charges, and specifically, the asymmetry between recombination pathways in positively and negatively charged QDs. Finally, we provide evidence for the direct relation of Auger recombination to the problem of LED efficiency roll-off (known also as a "droop" effect") at high driving currents, suggesting that the realization of high-performance LEDs might require a new generation of "Auger-decay-engineered" QDs that in addition to being efficient single-exciton emitters would also show high emission efficiency in the multicarrier regime.

9162-13, Session 4

Positioning of single quantum dots on nanoscale areas of metal-free substrates

Isabelle Staude, The Australian National Univ. (Australia); Varun K. A. Sreenivasan, Macquarie Univ. (Australia); Ivan Shishkin, Kirill Samusev, Ioffe Physico-Technical Institute (Russian Federation) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Manuel Decker, Dragomir N. Neshev, The Australian National Univ. (Australia); Andrei V. Zvyagin, Macquarie Univ. (Australia); Yuri S. Kivshar, The Australian National Univ. (Australia)

The coupling of colloidal semiconductor quantum dots (QDs) to subwavelength nanophotonic structures remains an active field of research [1]. For enhanced control over the optical properties of the coupled system, the positioning of QDs at specific locations of the photonic nanostructures is crucial. In particular, selective binding of QDs to the feed elements of plasmonic (metallic) nanoantennas has been demonstrated to allow for tailoring the directionality of QD emission [2]. However, the precise and controlled placement of single colloidal QDs with respect to metal-free all-dielectric photonic nanostructures by a scalable lithographic process still poses a major challenge. The demand for such a process is rapidly growing, driven by emerging research efforts into all-dielectric nanoantennas and all-dielectric metamaterials [3].

Here, we demonstrate a novel process for selective binding of single semiconductor core-shell quantum dots (QDs) to transparent all-dielectric (glass) substrates with nanoscale precision. This is accomplished by defining a mask via electron-beam lithography (EBL) followed by functionalization of only the exposed areas of the substrate with a heterobifunctional linker, while applying a binding inhibitor to

all other areas. Single QD blinking is clearly observed for several QD functionalized sites. Our approach is compatible with standard two-step EBL nanofabrication schemes and it does not rely on the presence of metals, making it suitable for coupling QDs to various nanoresonators, including dielectric-only systems.

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9162-14, Session 4

Photons-on-demand: synthesis and integration strategies for non-blinking giant quantum dots *(Invited Paper)*

Jennifer A. Hollingsworth, Han Htoon, Krishna Acharya, Niladri S. Karan, Mathew R. Buck, Farah Dawood, Hue M. Nguyen, Aaron M. Keller, Los Alamos National Lab. (United States)

Bright, stable emitters are needed for the range of applications from bio-imaging and molecular tracking to solid-state lighting and single-photon sources for quantum information processing. We have previously demonstrated ultrastable single-emitter level photoluminescence in non-blinking and non-photobleaching thick-shell CdSe/CdS [1] and InP/CdS [2] core/shell colloidal quantum dots. The remarkable properties of these nanoscale emitters were initially attributed to an unusually thick CdS shell, inspiring the designation of "giant" quantum dots.[3] We have since shown that in addition to shell thickness, core size, electronic structure and/or core/shell interfacial properties can strongly influence the processes that impact blinking behavior – charging and nonradiative Auger recombination. With these various 'design parameters' in mind, we are synthesizing a range of quantum dot heterostructures targeting similar single-dot stability across the visible and into the near-infrared. I will review our recent progress in meeting the strict requirements for single-dot photostability for green, red and near-infrared emitting quantum dots. I will also discuss how we are coupling these 'active' photonic materials with plasmonic or dielectric components to enhance or modify exciton recombination processes. Specifically, we have developed synthetic methods to fabricate semiconductor giant quantum dot-metal hybrid heterostructures, while we have used a 'direct-write' nanolithography approach to integrate colloidally synthesized quantum dots with pre-fabricated structured photonic materials. In both cases, we can achieve nanoscale integration for enhanced or modified emission properties.

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9162-15, Session 5

Isotropic band gaps, optical cavities, and freeform waveguides in hyperuniform disordered photonic solids *(Invited Paper)*

Marian Florescu, Univ. of Surrey (United Kingdom); Weining Man, San Francisco State Univ. (United States); Ruth Ann Mullen, Etaphase Inc. (United States); Milan M. Milosevic, Timothy Amoah, Univ. of Surrey (United Kingdom); Paul M. Chaikin, New York Univ. (United States); Salvatore Torquato, Paul Steinhardt, Princeton Univ. (United States)

Hyperuniform disordered solids are a new class of designer photonic materials with large isotropic band gaps comparable to those found in photonic crystals. The hyperuniform disordered materials are statistically isotropic and possess a constrained randomness such that density fluctuations on large scales behave more like those of ordered solids, crystals or quasicrystals, than like those of conventional amorphous materials. The hyperuniform disordered network structures are designed by employing a centroidal tessellation of a hyperuniform point pattern to generate a "relaxed" dual lattice, whose vertices are necessarily trihedrally coordinated. Our simulations show that slab architectures of Si based hyperuniform disordered networks display photonic bad gaps of at least 20%. Optical cavities introduced in these materials support localized modes with high quality factors and a variety of symmetries. The isotropy of the PBG unique to hyperuniform disordered structures, enables designer waveguides of essentially arbitrary shape, along which the light can be guided through the excitation of localized resonances similar to the ones that we found in the point-like defects. Using standard electron beam lithography and inductively-coupled plasma reactive ion etching we have fabricated hyperuniform disordered structures with an average lattice constant of 500nm and wall thickness of 100nm. Furthermore, our experiments demonstrate photonic band gaps and low-loss wave-guiding in submicron scale Si-based hyperuniform structures operating at in the 1550nm wavelength range and open the way for the realization of highly flexible, disorder-insensitive optical micro-circuit platforms.

9162-16, Session 5

Qualitative models in nanophotonics

Arkadi Chipouline, Friedrich-Schiller-Univ. Jena (Germany)

Recent technological advancements allowing creation of nanoobjects/metamaterials in the optical domain has forced the revisiting of basics electrodynamic principles and assumptions. A large amount of new experimental and theoretical data has to be structured within the framework of a new unified approach, in order to distinguish the really fundamental knowledge from various applications and particular cases. A unified approach appears to be extremely important for educational courses in the area of nanophotonics/optical metamaterials. In particular it allows us to present a self-consistent physical picture, which in turn minimizes the amount of educational material to be memorized to the crucial physics.

The results of analytical, numerical, and experimental investigations of the resonantly coupled dynamics of the classical system (strip resonator, plasmonic nanoresonator) and quantum systems (Josephson Junction (JJ), quantum dots, dye molecules, etc.) are presented. The wide range of the physical phenomena appearing in these coupled system, is analysed in the frame of the unified approach. The following problems will be considered:

1. Regular and stochastic characteristics (radiation linewidth) of the nanolasers (such as the spaser).

2. It is shown that direct application of Schawlow-Townes expression overestimates the linewidth and has to be avoided at the description of the nanolaser. Analytical results are compared with ones obtained from the direct numerical simulation of the dynamics of the laser equations.

3. A model for anapole laser will be presented.

4. Propagation of the plane wave in a metamaterial with gain (metaatoms in form of spasers) is considered using the developed earlier multipole model and the results of the spaser dynamics. It is shown that the stable propagation is possible if ratio of the coupled and uncoupled active molecules is chosen carefully.

5. The problems of the luminescent enhancement and life time shortening are analysed in the frames of the developed approach and compared with the experimental data.

9162-17, Session 5

Beam shaping and manipulation in photonic crystal structures *(Invited Paper)*

Anna C. Tasolamprou, Foundation for Research and Technology-Hellas (Greece); Lei Zhang, Iowa State Univ. (United States); Maria Kafesaki, Foundation for Research and Technology-Hellas

(Greece); Thomas Koschny, Costas M. Soukoulis, Iowa State Univ. (United States)

Photonic crystals (PCs) are well known materials mostly due to their band gap properties. Additionally is has been shown, both theoretically and experimentally, that PCs support the propagation of surface waves, provided that they are properly terminated. This termination consists of a corrugated outer periodic layer which may differ in shape and/or lattice constant from the bulk material. Introducing a line defect acting as a waveguide in a bulk photonic crystal structure and properly designing the corrugated layer enables the excitation of the surface states within the band gap. The surface layer alone leads to reduced transmission efficiency along the waveguide axis; nevertheless an additional grating like-layer may facilitate the coupling of the surface waves to outgoing propagating waves. The surface energy radiation results in enhanced transmission and directionality of the beam. The key feature of this configuration is the grating layer which under specific conditions, leads to constructive interference of the diffracted waves and beaming. This work investigates and demonstrates how the proper design of the grating layer allows for selective interference and provides control over the beam shape and emission angle. Apart from the PCs, it has been discovered that even a single dielectric layer can support surface states, whereas a surface and grating bilayer may couple the surface states to outgoing propagating waves. Here we also demonstrate both experimentally and theoretically, that such a bilayer dielectric structure allows for the collimation and enhanced transmission of a Gaussian incident beam, while a system of multiple cascading bilayers can sustain the beam for large propagation distances.

9162-18, Session 6

CMOS integrated plasmonics: interconnects and modulators *(Invited Paper)*

Alexandra Boltasseva, Nathaniel Kinsey, Marcello Ferrera, Purdue Univ. (United States); Viktoriia E. Babicheva, DTU Fotonik (Denmark); Gururaj V. Naik, Stanford Univ. (United States); Alexander V. Kildishev, Vladimir M. Shalaev, Purdue Univ. (United States)

During the last decade, numerous designs have been proposed for the fabrication of fundamental nanophotonic devices such as waveguides, modulators, amplifiers, and photodetectors. All of which require high mode localization and the low propagation losses to maximize their performances. However, most of these structures use noble metals such as gold or silver, which are not CMOS-compatible, limiting their applicability. Recently, a great effort has been given in the search of alternative plasmonic materials. According to these studies, transition metal nitrides and transparent conducting oxides (TCOs) could represent promising platforms for future plasmonic devices. Among these materials, titanium nitride (TiN) is one of the best candidates because of its chemical stability, bio-compatibility and resistance to mechanical stress. In addition, it can be grown epitaxially on many substrates. TCOs offer the ability to vary their complex refractive indices over a broad range by modulating the carrier concentration with an external electric field. In this work, by using potentially CMOS-compatible plasmonic materials, we investigate a novel design for an ultra-compact modulator. Our modulator can achieve an extinction ratio of 46 dB/µm, an off-state mode size as small as 1.3 µm, and 3 dB modulation in just 65 nm of propagation length. The experimental characterization of TiN-based waveguides is also presented as the first step towards an integrated plasmonic modulator. Our guiding structures show propagation losses < 0.79 dB/mm. Both the modulator and waveguide are potentially CMOS compatible. These results demonstrate the ability of future CMOS compatible nanophotonic devices

9162-19, Session 6

Printing high-quality tunable porous silicon microcavities *(Invited Paper)*

Paul V. Braun, Neil A. Krueger, Hailing Ning, Univ. of Illinois at Urbana-Champaign (United States)

Porous silicon (PSi) became a material of interest in the early 1990's with its ability to emit visible light. Since that time, PSi has demonstrated potential beyond light emission and gained an identity as a versatile optical material because of its inherent refractive index modulation capabilities achieved by either porosity variation or porosity infiltration. Porosity variation produces high-quality optical superlattices (e.g. microcavities), which feature optical resonances that control the light-matter interaction of light-emitters located inside the cavity and can simultaneously be tuned by pore infiltration. However, all such attempts with PSi monolithic microcavities have been fundamentally limited to emitters integrated into the porous network. Hybrid microcavities could extend the scope of compatible emitters, but grafting fragile, free-standing PSi films without damage has been an obstacle to realizing high-quality structures. Here, we demonstrate that PSi photonic components, when coupled with a modified transfer-printing technique, enable the formation of high-quality hybrid microcavities that are compatible with all forms of external emitters. Further, we provide a means to utilize PSi's refractive index modulation capabilities in the hybrid microcavity, allowing us to both globally tune and spatially modulate the resonant mode of the resulting structure.

9162-20, Session 6

Metal oxides as tunable photonic materials *(Invited Paper)*

Otto L. Muskens, Univ. of Southampton (United Kingdom)

Highly doped metal oxides behave like Drude metals in the infrared and transparent dielectrics in the visible. We show that a wide range of optical properties can be achieved of interest for applications in photonics, ranging from tunable dielectrics for hybrid plasmonic devices [1], to epsilon-near-zero response [2] and plasmonic behavior in the infrared [3]. Epsilon-near-zero behavior includes total external reflection and air guiding of light using metal oxide cladded waveguides. Ultrafast control of metal-oxide hybrid photonic structures, exploiting picosecond modulation of the free carrier density, is demonstrated which opens up avenues for new active photonic devices.

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9162-21, Session 6

Strong coupling of delocalized and localized resonances in voltage tunable terahertz 2D plasmonic crystals *(Invited Paper)*

Gregory C. Dyer, Sandia National Labs. (United States); Gregory R. Aizin, Kingsborough Community College (United States) and The City College of New York (United States); S. James Allen Jr., Univ. of California, Santa Barbara (United States); Albert D. Grine, Don Bethke, John L. Reno, Eric A. Shaner, Sandia National Labs. (United States)

Low dimensional plasmonic systems based on III-V compound semiconductor heterostructures and graphene have garnered significant attention for their application in terahertz (THz) detectors, mixers, oscillators and modulators. Of particular interest is the broad tunability of underdamped plasma excitations in these two-dimensional (2D) plasmonic systems. Here we illustrate the rational design of voltage tunable THz plasmonic crystals using sequential coupled GaAs/AlGaAs 2D plasmonic resonators as the basic building block. Much like a metamaterial element, the studied structures are subwavelength, yet nonetheless Bragg scatter plasma waves from a repeated crystal unit cell.

We electronically detect the spectrum of coupled 2D plasmonic micro-resonator structures at cryogenic temperatures. Using a plasmonic homodyne mixing mechanism to downconvert the near field of plasma waves to a DC signal, a 50% in situ tuning of the plasmonic crystal band edges is observed. Breaking of a plasmonic crystal's translational symmetry introduces localized plasmonic resonances to the measured spectra. Due to the coupling of localized defect modes with crystal surface states known as Tamm states and the inherent asymmetries in the device structures, we observe an induced transparency-like phenomenon. These experimental results are interpreted and validated using an equivalent circuit formulism where the field effect tunable kinetic inductance of quantum confined electrons has a dominant contribution. The active control of coupled plasmonic resonators demonstrated in this work suggests new paths for the development of ultra-sensitive direct and heterodyne THz detectors, planar metamaterials, and slow-light devices.

9162-22, Session 7

Dielectric and metallic nanosuspesions with tunable optical nonlinearities *(Invited Paper)*

Zhigang Chen, Nankai Univ. (China) and San Francisco State Univ. (United States); Demetrios N. Christodoulides, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

In recent years, the development of artificial materials exhibiting novel optical properties has become one of the major scientific endeavors. Of particular interest are soft-matter systems, which play a central role in numerous fields ranging from life sciences to chemistry and physics. In this talk, we will present two types of soft-matter systems with tunable optical nonlinearities. The first one is the colloidal dielectric suspensions while the second is the metallic suspension. In both systems, by appropriately engineering the polarizability of the nanosuspensions, we can alter at will the nonlinear light-matter interactions in order to overcome the effects from diffraction and scattering, hence to achieve deep beam penetration through the colloids. In particular, we have deliberately synthesized colloidal suspensions with negative polarizabilities by suspending polytetrafluoroethylene (PTFE) particles in a diluted glycerin-water solution, and we have observed robust propagation and enhanced transmission of self-trapped light through such scattering media. In addition, we show that plasmonic nanoparticles provide a versatile platform for controlling the flow of light in soft-matter systems. Due to resonant nature of the light-matter interaction in metallic nanosuspensions, we have observed self-trapping and robust soliton propagation of light over distances up to 25 diffraction lengths, which would have been otherwise impossible in conventional dielectric settings. Our findings may bring about solutions to overcome large scattering loss and to pave the avenue for engineering various soft matter systems with tunable nonlinearities, promising for various applications including optical trapping and manipulation as well as initiation of chemical reactions.

9162-23, Session 7

Ultrafast reconfigurable photonic devices using dynamic wavefront shaping

Otto L. Muskens, Thomas Strudley, Roman Bruck, Univ. of Southampton (United Kingdom)

Wavefront shaping has enabled the use of opaque scattering media as versatile and reconfigurable optical elements. Here we demonstrate ultrafast control of a shaped light field exploiting a combination of wavefront shaping and ultrafast nonlinearity of the host medium. We identify a new regime of ultrafast phase control, which can be used to effectively dephase the shaped wavefront, resulting in a modulation of up to 63%. This phase dynamics can be partially inverted to produce a dynamical reshaping of the light field and a transient increase of the peak intensity of an optimized wavefront by as much as 20%.

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9162-24, Session 7

Nonlinear frequency generation from Si/Chalcogenide glass hybrid waveguides by degenerate four wave mixing

Jörg Schilling, Martin-Luther-Univ. Halle-Wittenberg (Germany); Peter W. Nolte, Martin-Luther-Univ. Halle-Wittenberg (Germany) and Fraunhofer-Institut für Werkstoffmechanik (Germany); Georg von Freymann, Technische Univ. Kaiserslautern (Germany); Mark McMillen, Queen's Univ. Belfast (United Kingdom)

Recent successes in the area of efficient four wave mixing (FWM) in SiN- and Hydex-waveguides have triggered a plethora of further work on frequency comb generation and the applications for ultrashort pulses. However due to the limited third order nonlinearity (n2) of SiN and Hydex, the structures have a large footprint and a high power input is necessary. The chalkogenide glass As2S3 on the other hand promises a nearly 10 times larger n2 and a nonlinear figure of merit (FOM) of 215 for telekom wavelengths, although the fabrication of low loss As2S3-waveguides still presents a challenge.

Here we demonstrate the combination of the superior waveguiding properties of Si with the high nonlinear FOM of As2S3 in form of an infiltrated Si slot waveguide, applying standard CMOS technology and a subsequent nano-injection molding process to infiltrate the 100nm wide slot with As2S3. Several race track resonators are formed to create a structure of small footprint and efficiently enhance the degenerate four wave mixing process. NIR radiation is supplied by two tunable cw-lasers via lensed fibres which are butt-coupled to the Si feeding waveguide.

From low power transmission measurements Q-factors of 10^5 were obtained for the race track resonators. An evaluation of the free spectral range yields a group index of ng=3.4 and a group velocity dispersion of -3300ps/(nm km). Feeding a pump power and signal power of 10mW and 5mW in neighbouring resonances, degenerate four wave mixing within the race track resonators was observed leading to the formation of idler waves with a conversion efficiency of -40dB. A frequency sweep of the signal wave emphasizes the importance of a vanishing group velocity dispersion for enhanced efficient FWM. Furthermore alternative waveguide designs (Bragg-waveguides) and possibilities for quasi phase matching within the resonator are discussed.

These results represent an important step towards hybrid active photonic devices combining the optical nonlinearity of chalcogenide glasses with silicon photonics.

9162-25, Session 7

Medium-dependent resonance energy transfer: a controlling role for three-centre upconversion

Jamie M. Leeder, David L. Andrews, Univ. of East Anglia (United Kingdom)

Upconversion (UC) generally refers to any nonlinear optical process that facilitates conversion of low energy radiation into higher energy emission. Typically achieved in materials incorporating rare-earth ions, exploiting their rich density of available electronic state transitions, non-parametric UC systems are often placed in categories including excited state absorption (ESA), photon avalanche (PA) and energy transfer (ET). The latter, energy transfer upconversion (ETUC) achieves nonlinear excitation of a chromophore as a consequence of one or more non-radiative resonance energy transfer (RET) events, through coupling with neighbouring sensitizer ions. Being susceptible to the local electromagnetic environment, the mechanism of RET is known to be influenced by surrounding matter, underscoring the importance of similar channels for media control within ETUC materials.

Developing the principles of two-centre RET, a fully quantized representation of local electronic structure and electrodynamics is extended by the introduction of a mediator species – a vicinal, non-absorbing chromophore. This theory underpins a new application of the medium-modified energy transfer theory to three-centre RET. The present report focuses on upconversion in which two identical donors transfer energy to an acceptor, promoting two-photon excitation and shorter wavelength emission. The mechanism for this three-centre system proves to be significantly influenced by a fourth, essentially passive chromophore. Investigations of the influence of this mediator, in improving or inhibiting RET, determine parameters that can be optimized to improve the UC efficiency. The results provide insight into factors that might assist the optimization of laser active media, and the improvement of optical characteristics in novel designer materials.

9162-26, Session 8

Novel phenomena in nano-photonic systems of macroscopic sizes *(Invited Paper)*

Marin Soljacic, Massachusetts Institute of Technology (United States)

Nanophotonic techniques can enable numerous novel and exciting phenomena. However, in order to make use of these opportunities for many applications of interest (e.g. energy, or displays), one has to have the ability to implement nanophotonic structures over large scales. In this talk, I will present some of our recent theoretical and experimental progress in exploring these opportunities.

9162-27, Session 8

Nanophotonics with nanomaterials: a route for functional photonic integration *(Invited Paper)*

Atsushi Yokoo, M. D. Birowosuto, Masaya Notomi, NTT Basic Research Labs. (Japan)

To realize low-power photonic-integration, it is important to implement functional materials with small volume because the active size determines the power consumption. However, such heterogeneous integration is difficult. One possible way is to employ nanomaterials for building blocks for photonic integration, but. they are usually less efficient because their size is much smaller than the wavelength of light. In this talk, we show that a combination of nanomaterials with well-designed nanophotonic systems enables strong interaction between nanomaterials with photons. We demonstrate a high-Q nanocavity consisting of an sub-wavelength III/V nanowire coupled with a Si photonic crystal, which realizes unprecedented strong light confinement in a nanowire. We discuss related technologies and possible impacts for future photonic integration.

9162-28, Session 8

Fabrication and characterization of optical cavities and integrated photonics structures on GaN-based photonic crystal membranes grown on silicon for visible and near infra-red applications *(Invited Paper)*

Romuald Houdré, Noelia Vico Triviño, Ulagalandha Dharanipathy, Jean-François Carlin, Nicolas Grandjean, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

The development of waveguides and photonic crystal (PhC) waveguides has been a topic of intense research effort during the past few years. Most of conventional waveguides are fabricated on Si using silicon-on-insulator technology. However, it is intrinsically limited to near infrared applications. Owing to its near-UV bandgap, GaN is transparent in the visible range, and is an ideal candidate for visible range applications such as bio-photonics and fluorescence-based systems. III-nitrides are also potentially suitable for operation around 1.5 µm. They offer low free carrier absorption and negligible two-photon absorption. They also exhibit a considerable mechanical hardness and a high thermal stability of the refractive index, which is one order of magnitude larger than that of InP. Furthermore, III-nitride epilayers have already been grown on silicon substrates with device quality, as shown by the fabrication of high-efficiency blue light emitting diodes. Actually, GaN on silicon may offer a unique template for integrated photonics.

The fabrication and characterization of freestanding hybrid GaN photonic structures operating at 1.55 µm or in the visible range will be discussed. The structures are self-supported by tethers and coupled to photonic crystal waveguides and cavities. The fabrication process is based on the growth of GaN on Si, e-beam lithography and dry etching. W1 PhC waveguides and L3 cavities are investigated. The cavities exhibit quality factors as high as ~ 5400. In the visible range, L7-type cavity with InGaN/GaN quantum wells exhibit modes with Q factors up to 5200 at ~ 420 nm at 10 K.

9162-29, Session 8

Diamond photonics *(Invited Paper)*

Marko Loncar, Harvard School of Engineering and Applied Sciences (United States); Michael J. Burek, Birgit M. Hausmann, Harvard Univ. (United States); Vivek Venkataraman, Harvard School of Engineering and Applied Sciences (United States)

In my talk I will review recent advances in nanotechnology that have enabled fabrication of nanoscale optical devices and chip-scale systems in diamond. Applications ranging from quantum optics and nonlinear optics, to optomechanics will be discussed.

9162-30, Session 9

Graphene plasmons: properties and applications *(Invited Paper)*

Phaedon Avouris, Damon B Farmer, Marcus Freitag, IBM Thomas J. Watson Research Ctr. (United States); Yielei Li, Columbia Univ. (United States); Tony Low, Hugen Yan, Han Wang, IBM Thomas J. Watson Research Ctr. (United States)

I will discuss the optical properties and possible applications of graphene in photonics and plasmonics. I will review the basics of the single particle and collective excitations of graphene, discuss the mechanisms of photocurrent generation in graphene and the design and characteristics of graphene-based photodetectors. I will show that the coupling of light to localized graphene plasmons provides an excellent way of enhancing the strength of graphene-light interaction. Plasmon excitations

in graphene micro- and nano-structures and their use in graphene devices in the infrared and terahertz ranges of the EM spectrum will be discussed. The interactions of graphene plasmons with intrinsic graphene and substrate phonons and their implications will also be analyzed.

9162-31, Session 9

2D nano-optoelectronics *(Invited Paper)*

Thomas Mueller, Andreas Pospischil, Marco M. Furchi, Technische Univ. Wien (Austria)

Two-dimensional (2D) atomic crystals, such as graphene and atomically thin transition metal dichalcogenides (TMDCs), are currently receiving a lot of attention. They are crystalline, and thus of high material quality, even so, they can be produced in large areas and are bendable, thus providing opportunities for novel applications. In this talk, a 2D p-n junction diode based on an electrostatically doped tungsten diselenide (WSe2) atomic monolayer will be presented. As p-n diodes are the basic building block in a wide variety of optoelectronic devices, our demonstration constitutes an important advance towards 2D optoelectronics. Applications as photovoltaic solar cell, photodiode, and light emitting diode will be discussed.

9162-32, Session 9

Short-pulse fiber lasers mode-locked by carbon nanotube and graphene *(Invited Paper)*

Shinji Yamashita, The Univ. of Tokyo (Japan); Sze Y Set, Bo Xu, Alnair Labs Corporation (Japan)

We review the optical properties of carbon nanotubes (CNTs) and graphene and describe how those properties have been used for the implementation of various nonlinear fiber optic applications. Early studies on the optical properties of CNTs in the late 90s revealed that these materials exhibit high third order susceptibility and a broadband saturable absorption with a sub-picosecond response time. Recent discovery of similar nonlinear optical properties in graphene attracts much attentions in this field. Such ultrafast, highly nonlinear optical response means that they can be employed for noise suppression and for the mode-locking of fiber lasers, and in addition, their high third order nonlinearity holds great promise for the implementation of various other nonlinear fiber optic devices such as wavelength converters based on four wave mixing. In this paper, we will discuss the various methods that have been considered thus far for the integration of CNTs and graphene in optical systems and highlight the advantages and limitations of using the saturable absorption of CNTs and graphene for the passive mode-locking of fiber lasers, and the current status of CNT and graphene saturable absorbers in the state of art fiber laser technologies.

9162-33, Session 10

Quantum plasmonics: plasmon induced processes *(Invited Paper)*

Peter Nordlander, Rice Univ. (United States)

Plasmon energies can be tuned across the spectrum by simply changing the geometrical shape of a nanostructure. Plasmons can efficiently capture incident light and focus it to nanometer sized hotspots which can enhance electronic and vibrational excitations in nearby structures.[1] For narrow plasmonic junctions, quantum mechanical effects can play an important role: the large field induced in the junction can facilitate electron tunneling and charge transfer[2] and also lead to nonlinear optical response.[3] Another important but still relatively unexplored effect is production of hot energetic electrons which can transfer into nearby structures and induce a variety of processes. This process is a quantum mechanical effect: the decay of plasmon quanta into electron-hole pairs. I will discuss how plasmon induced hot electrons can be used in various applications: such as to induce chemical reactions in molecules physisorbed on a nanoparticle surface;[4] to inject electrons directly into the conduction band of a nearby substrate;[5] and to induce local doping of a nearby graphene sheet.[6]

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9162-34, Session 10

Hybrid graphene-silicon photonic integrated circuits *(Invited Paper)*

Dirk R. Englund, Ren-Jye Shiue, Cheng Peng, Massachusetts Institute of Technology (United States)

There has been a rapidly growing interest in graphene-based optoelectronics. This exceptional material exhibits broadband optical response, ultrahigh carrier mobility and more importantly, potential compatibility with silicon complementary metal-oxide semiconductor (CMOS) technology. We describe our recent results on integrated hybrid graphene-silicon photonic systems. One of the central advantages of such nanophotonic structures, such as cavities and waveguides, is the ability to greatly enhance the absorption into graphene, from the low single-pass value of 2.3% to nearly 100%. In particular, by coupling graphene to an optical cavity, we demonstrated an efficient electro-optic modulator that features a modulation depth of 10 dB and a switching energy of just 300 fJ. High-speed modulators now reach rates beyond the GHz mark. We will also describe the implementation of graphene photodetectors on silicon waveguide. These show a responsivity beyond 300 mA/W. Data transmission rates in excess of 12 Gbps and response times above 20 GHz are achieved. These results show the feasibility of graphene as a building block for silicon photonic integrated circuits. In particular, on-chip graphene active devices such as modulators and photodetectors are promising for their broadband response, high-speed operation, low power consumption and ease-to-fabrication.

9162-35, Session 10

Plasmon-phonon coupling in graphene nanostructures *(Invited Paper)*

N. Asger Mortensen, DTU Fotonik (Denmark)

Nanostructured graphene on SiO2 substrates pave the way for enhanced light-matter interactions and explorations of strong plasmon-phonon hybridization in the mid-infrared regime. In particular, the structural control over localized graphene plasmons can be used to map out the hybridization of plasmon and phonon modes. Unprecedented large-area graphene nanodot and antidot optical arrays are fabricated by nanosphere lithography, with structural control down to the sub-100 nanometer regime. The interaction between graphene plasmon modes and the substrate phonons is experimentally demonstrated and variation of the nanodot diameter is used to map out the hybridization of plasmons and phonons, showing coupling energies of the order 20 meV. Our findings are further supported by theoretical calculations and numerical simulations.

9162-36, Session 10

2D materials for strong light-matter interactions at nanometer lengthscales and ultra-fast timescales *(Invited Paper)*

Frank H. Koppens, ICFO - Institut de Ciències Fotòniques (Spain)

Optics and opto-electronics of graphene is one of most vibrant, rapidly developing and exciting areas which has already led to some commercial applications. Rather than being just another new photonic material, it combines a wide palette of unique aspects which promise breakthroughs in several outstanding problems of nanophotonics and optoelectronics, including broadband photodetection and sensing, on-chip manipulation of nanoscale optical fields and lasing.

In this talk, the most recent developments of graphene nano-photonics, plasmonics and photoconversion for near-infrared and infrared frequencies are being reviewed. Strong interactions between graphene and nanoscale light-emitters are actively controlled and detected by tuning graphene from an absorbing to plasmonic material. Graphene plasmons, which allow for strong confinement of optical fields are visualized in real space and gate-tunability and long propagation lengths are demonstrated by employing high mobility graphene.

9162-37, Session 11

Molecular bond Fano resonances in organic thin films enhanced by (A)SRR arrays *(Invited Paper)*

Richard M. De La Rue, Ifeoma G. Mbomson, Saima I. Khan, Graham J. Sharp, Basudev Lahiri, Nigel P. Johnson, Univ. of Glasgow (United Kingdom); Henrique Vilhena, Scott G. McMeekin, Glasgow Caledonian Univ. (United Kingdom)

This presentation will be concerned with nanophotonic structures, in particular asymmetric split-ring resonator (ASRR) structures, that may be exploited in sensing applications. In particular, these applications include bio-medical sensing, organic material sensing more generally - and environmental sensing. Specific attention will be paid to identification of specific molecules of interest via their bond Fano-resonance signatures.

9162-38, Session 11

Spectrally selective chiral silicon metasurfaces based on infrared fano resonances *(Invited Paper)*

Gennady B. Shvets, The Univ. of Texas at Austin (United States)

Metamaterials and metasurfaces represent a remarkably versatile platform for light manipulation, biological and chemical sensing, and nonlinear optics. Many of these applications rely on the resonant nature of metamaterials, which is the basis for extreme spectrally selective concentration of optical energy in the near field. In addition, metamaterial-based optical devices lend themselves to considerable miniaturization because of their sub-wavelength features. This additional advantage sets metamaterials apart from their predecessors, photonic crystals, which achieve spectral selectivity through

their long-range periodicity. Unfortunately, spectral selectivity of the overwhelming majority of metamaterials that are made of metals is severely limited by high plasmonic losses. Here, we propose and demonstrate Fano-resonant all-dielectric metasurfaces supporting optical resonances with quality factors that are almost an order of magnitude sharper than those supported by their plasmonic counterparts. We also demonstrate that these silicon-based metasurfaces exhibit extreme planar chirality, opening exciting possibilities for efficient ultra-thin circular polarizers and narrow-band thermal emitters of circularly polarized radiation.

9162-39, Session 11

Complex chiral colloids for visible and ultraviolet plasmonics *(Invited Paper)*

David J. Norris, ETH Zürich (Switzerland)

Because nanoparticles have properties strongly influenced by their shape, various routes to complex geometries have been developed. Despite these advances, chiral shapes, those not superimposable on their mirror image, remain challenging. Aggregates and helices with chirality are possible, but not other shapes critical for sensing, catalysis, and nonlinear optics. Solid particles with strong optical chirality at ultraviolet wavelengths could also enhance detection of chirality in biomacromolecules. Here, we will discuss recent efforts to prepare chiral nanoparticles. We have been exploiting anisotropic etching of silicon wafers to create solid chiral plasmonic nanopyramids of a specific handedness. The resulting particles, which are dispersed into liquids as colloids, present chiral pockets for molecular binding whilst their tips allow exploration of superchiral electromagnetic fields. Made from gold, they exhibit record circular dichroism at red wavelengths. From aluminum, ultraviolet chirality resonant with biomolecules is obtained. Thus, in addition to other applications, they allow new routes to detecting structural chirality in chemistry and biology.

9162-75, Session 11

Shear ordering of densely packed core-shell spheres in super viscoelastic medium for making 3D photonic crystals

Qibin Zhao, Andrew I. Haines, David R. E. Snoswell, Univ. of Cambridge (United Kingdom); Chris E. Finlayson, Aberystwyth Univ. (United Kingdom); Christian Schaefer, Darmstadt Univ. of Technology (Germany); Peter Spahn, CACI International, Inc. (United States); Lars O. Herrmann, Jeremy J. Baumberg, Univ. of Cambridge (United Kingdom)

Making photonic crystals on large scale remains highly problematic, despite their great utility for manipulating light. We have been developing routes to polymer opals, which are stretchable 3D photonic crystals comprised of densely-packed ordered core-shell spheres. Here we demonstrate their fabrication on the kilometre-scale using a novel bottom-up bending-induced oscillatory shearing (BIOS) process.

Shearing has been widely studied yet not fully understood in both granular physics and colloidal science. Compared to most granular or colloidal systems which use a liquid inter-particle medium with low viscosity which thus has little influence, our shearing assembly works with densely-packed polymer spheres in a highly viscoelastic medium. The spheres, with a hard polystyrene core and a low Tg soft sticky polyethylacrylate shell, are pressed into thin films sandwiched between two rigid plastic foils, then sheared in the solid phase using BIOS technique. By banding the sandwiched film onto heated rollers and driving the film backward and forward repeatedly, oscillatory lateral is applied homogeneously across the whole film, and high quality flexible 3D photonic crystal films of length scale up to 1km are obtained. Optical reflection and transmission properties of the photonic crystals show the influence of processing in one direction (uni-axial BIOS) or two directions (bi-axial BIOS, 30° with respect to each other) for different numbers of passes. This is confirmed by using micro-radian x-ray scattering, which demonstrates how the in-plane and inter-plane arrangements of spheres evolves. Such polymer photonic crystals have a wide range of uses in healthcare, coatings and security applications.

9162-40, Session 12

Light trapping and solar energy harvesting in thin-film photonic crystals *(Keynote Presentation)*

Sajeev John, Univ. of Toronto (Canada)

We describe designs of 3D photonic crystal silicon-based solar cells that enhance the overall absorption of sunlight using architectures consisting of less than 1 micron (equivalent bulk thickness) of silicon. This arises from light-trapping in the higher bands of a photonic crystal, where the electromagnetic density of states is enhanced rather than suppressed. This enables unprecedented strong absorption of sunlight in a material with weak intrinsic absorption.These crystals trap light through a parallel-to-interface negative refraction (PIR) effect and other optical resonances that occur over a broad angular and frequency range. These 3D photonic crystals exhibit slow group velocity modes, in which the flow of energy is transverse to the depth of a thin film of material. In the case of a modulated nano-wire photonic crystal solar cell, it is possible to absorb roughly 75% of all available sunlight in the wavelength range of 400-1100 nm, using one micron of silicon. In the case of conical nano-pore silicon photonic crystal, roughly 85% of all available sunlight is absorbed and power conversion efficiency in the range of 17.5%-22.5% is predicted. With combined plasmonic and photonic crystal light trapping, the fraction of absorbed sunlight exceeds 90%. The power conversion efficiencies of these sub-micron photonic crystals rival those of present-day solar cells using up to 300 microns of silicon. These photonic crystals offer additional opportunities for solar spectral reshaping to rival and possibly surpass the Shockley-Queisser power conversion efficiency limit.

9162-41, Session 12

Absorption in photonic crystals: from order to disorder *(Invited Paper)*

Christian Seassal, Loic Lalouat, He Ding, Emmanuel Drouard, Guillaume Gomard, Romain Peretti, Thierry Deschamps, Institut des Nanotechnologies de Lyon (France); Fabien Mandorlo, Régis Orobtchouk, INL-CNRS-INSA Lyon (France); Alain Fave, Institut National des Sciences Appliquées de Lyon (France)

The maturity of nanophotonics has triggered the emergence of novel concepts for light trapping in photovoltaic solar cells. Such novel approaches are based on various promising nanostructures, including planar 2D photonic crystals, and their abilities to control light propagation and photon capture.

While strictly mono-periodic photonic crystals enable to achieve high absorption in limited spectral ranges, introducing a controlled degree of disorder offers an efficient way to substantially increase the integrated absorption, and finally the generated photocurrent. In this communication, we will first introduce the nanophotonic engineering concepts, and the methodologies used to design and fabricate photonic crystal assisted solar cells, based on thin or ultra-thin c-Si and a-Si:H layers. Then, we will discuss on the potential of absorption increase using multi-periodic and pseudo-disordered photonic crystals. The enhanced absorption in such complex structures is achieved thanks to the optimized coupling of the incident light into a large number of modes in the spectral range of interest.

The use of such nanophotonic concepts is thus expected to greatly increase the efficiency of moderate cost thin film solar cells. Additionally, when combined with up- or down-conversion processes, these concepts can also be at the basis of ultra-high efficiency 3rd generation solar cells.

In this communication, we will present an overview of these nanophotonic concepts. This will be illustrated by examples, with a particular focus on the emergence of photonic crystals-assisted thin film silicon solar cells.

9162-42, Session 12

All-semiconductor IR broadband superabsorbers

G. Chinna R. Devarapu, Stavroula Foteinopoulou, Univ. of Exeter (United Kingdom)

Traditional absorbing architectures involves sandwiching the absorbing medium between an anti-reflector that enhances the in-coupling of the impinging light and a back-reflector that enhances the interaction between light and the absorbing matter. Current research directions in absorption management involve impedance-matched metamaterials for antireflection or plasmonic resonances for harnessing strong interaction between light and absorber. Here we demonstrate an all-semiconductor one-step superabsorber paradigm that is judiciously structured to simultaneously facilitate both a strong in-coupling and interaction of light with the semiconductor absorber leading to a near-perfect absorption over a broad IR spectral range.

9162-43, Session 12

Multi-dielectric stacks as a platform for giant optical field *(Invited Paper)*

Aude L. Lereu, Myriam Zerrad, Institut Fresnel (France); Marlène Petit, Frédérique De Fornel, LICB, UMR CNRS 5209 (France); Claude Amra, Institut Fresnel (France)

Multi-dielectric thin films can be analytically optimized with the admittance formalism to reach 100% absorption despite the low imaginary indices (some 10-5) of dielectric materials. Such optimization hence provides large optical field enhancements [1]. Theoretically, the enhancement should not be bounded if one does not consider non-linear aspects or optical damage. Indeed the field enhancement is conversely proportional to the imaginary part of the index of refraction. However this enhancement requires drastic illumination spectral and angular bandwidths [2], which constitutes a key limitation. Such multi-dielectric stacks were produced; one was optimized to be resonant with an enhancement factor equal to 1000, for a 633 nm illumination with an incidence of 45° and a TE polarization. Near field and far field measurements were then carried out to experimentally characterize the field enhancement [3, 4]. The differences with the predicted enhancement are explained by the experimental illumination conditions. We numerically evaluate the losses as a function of the light source spectral bandwidth and angular divergence [2].

We will first present our design method leading the fabrication of such multi-dielectric stacks, which can be optimized for arbitrary wavelengths, indices or polarizations. We will then report on our experimental characterization in near and far field, using a photon scanning tunneling microscope and scattering optical setup, respectively. Finally, we will numerically demonstrate the spectral and angular bandwidths essential to achieve the predicted field enhancement. This investigation may find applications for ultra-sensitive optical sensors or integrated light sources to mention a few.

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9162-44, Session 13

The opto-electronic physics which just broke the efficiency record in solar cells *(Keynote Presentation)*

Eli Yablonovitch, Univ. of California, Berkeley (United States);

Owen D. Miller, Massachusetts Institute of Technology (United States)

Suggested Reading: "Intense Internal and External Fluorescence as Solar Cells Approach the Shockley-Queisser Efficiency Limit", O. D. Miller, Eli Yablonovitch, and S. R. Kurtz, IEEE J. Photovoltaics, vol. 2, pp. 303-311 (2012).

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9162-45, Session 13

Light management and imaging for efficient light emitting and absorbing devices *(Invited Paper)*

Kai-Ming Ho, Iowa State Univ. (United States)

No Abstract Available

9162-46, Session 13

Controlling and creating plasmonic absorption processes in graphene nanostructures

Victor W. Brar, California Institute of Technology (United States) and Kavli Nanoscience Institute (United States); Min S. Jang, Seoul National Univ. (Korea, Republic of); Michelle Sherrott, Seyoon Kim, Laura Kim, California Institute of Technology (United States); ManSoo Choi, Seoul National Univ. (Korea, Republic of); Harry A. Atwater Jr., California Institute of Technology (United States)

Behaving as an extraordinarily thin waveguide, graphene has been recently shown to support electronically tunable ,Mid-IR plasmons with optical mode volumes that are 107 times smaller than freespace, and plasmon wavelengths more than 100 times shorter. In this presentation, it will be shown that the plasmonic absorption of a graphene sheet can be enhanced and perturbed in controllable ways by controlling the thickness and permittivity of the supporting substrate. We will show the results of recent experiments where 25% absorption is achieved in the plasmonic modes of a graphene sheet by carefully selecting the properties of an underlying silicon nitride substrate. We also demonstrate how additional absorption pathways can be created by modifying the surrounding dielectric environment to have optical resonances that can couple to the graphene plasmons. By placing graphene nanoresonators on a single layer boron nitride (BN) sheet new surface phonon plasmon polariton (SPPP) modes arise due to a strong coupling effect between the graphene plasmons and a BN optical phonon. We map the wavevector and doping dependence of these modes, and show that they display an anti-crossing behavior that indicates the strength of the coupling effect.

9162-47, Session 13

Plasmoelectric potentials in Au nano-hole arrays

Matthew T. Sheldon, California Institute of Technology (United States); Jorik van de Groep, FOM Institute for Atomic and Molecular Physics (Netherlands); Ana M. Brown, California Institute of Technology (United States); Albert Polman, FOM Institute for Atomic and Molecular Physics (Netherlands); Harry A. Atwater Jr., California Institute of Technology (United States)

The resonant plasmonic properties of metallic nanostructures depend strongly on charge carrier density. Stemming from this dependence, we have recently reported a theoretical framework and provided experimental evidence for a 'plasmoelectric effect', a newly described mechanism for generating electrochemical potentials in plasmonic nanostructures. Our initial work with Au colloid nanoparticles has shown that, unlike the more familiar thermoelectric or photovoltaic effects, the magnitude and sign of the plasmoelectric potential depends on the frequency difference between the plasmon resonance and incident radiation.

Here, we report measurements on lithographically patterned samples with a design that has been optimized via iterative full wave simulations to maximize plasmoelectric potentials. The structure consists of lithographically defined square-lattice arrays of 100nm diameter holes in a 20nm thick Au film. The plasmonic resonance is very sensitive to the inter-hole spacing, allowing sharp and highly tunable absorption peaks to be defined across the visible spectrum by varying the hole pitch. Scanning Kelvin probe force microscopy (KPFM) determined the surface potential of device structures while varying the incident wavelength. Under 30mW cm^-2 monochromatic illumination, we measure induced potentials of ± 150mV from hole arrays, with a characteristic sign change for illumination blue or red of the absorption maximum. This is a 2-order of magnitude increase compared with Au colloid particles, and consistent with our theoretical framework. Our findings guide the development of solid-state power conversion devices based on the plasmoelectric effect, as our devices generate electrochemical potentials 1000x larger than comparable thermocouples under equivalent optical power.

9162-48, Session 13

Theory of absorption-induced transparency *(Invited Paper)*

Sergio G. Rodrigo, Centro Univ. de la Defensa (Spain) and Instituto de Ciencia de Materiales de Aragón (Spain); Luis Martín-Moreno, Instituto de Ciencia de Materiales de Aragón (Spain)

Absorption induced transparency (AIT), roughly speaking, is a peak seen in the transmission spectrum of a holey metal film when a molecular dye is deposited on top of it [1]. An AIT peak appears unexpectedly close to one of the absorption energies of the molecules, hence its name. Tentative explanations of AIT pointed to strong-coupling interactions between Surface-Plasmon-Polaritons (SPPs) and molecules, when they are close by the metal surface (not inside the holes) [1]. However, we recently demonstrated the actual physical mechanism behind AIT [2]. This takes place through a strong modification of the propagation constant of holes, kz, so the holes must be at least partially filled. The spectral position of an AIT peak, its intensity and full width is mainly controlled by the spectral features of kz, AIT having thus a localized character, which also explains that it occurs in single holes.

In addition, we demonstrated that hole arrays in the AIT regime behave like a metamaterial characterized by a dielectric constant composed by a Drude plasma term (of geometric origin) plus a Lorentz term due to the molecules. We shown that AIT peaks are nonplasmonic in character, so they are expected at frequency regimes other than the optical, what opens the door for detection spectroscopy of chemical compounds with sharp absorption lines in the THz or microwave regimes.

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9162-49, Session 14

Meta-detectors for 4th generation infrared imagers *(Invited Paper)*

Sanjay Krishna, Ctr. for High Technology Materials (United States)

Mid infrared imagers are poised for the 4th generation of imagers. There is an increased emphasis on obtaining detectors with enhanced dynamic functionality at the pixel level. Meta-infrared detectors in which infrared detectors are combined with meta-structures are a promising way to realize this. The infrared region is appealing due to the low metallic loss, large penetration depth of the localized field and the larger feature sizes compared to the visible region. We will discuss approaches to realize multicolor detectors using these approaches.

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9162-50, Session 14

Design of highly directional and narrowband infrared emitters

Christopher H. Granier, Louisiana State Univ. (United States); Francis O. Afzal, Truman State Univ. (United States) and Louisiana State Univ. (United States); Changjun Min, Nankai Univ. (China) and Louisiana State Univ. (United States); Jonathan P. Dowling, Georgios Veronis, Louisiana State Univ. (United States)

Bulk thermal emittance sources possess incoherent, isotropic, and broadband radiation spectra that vary from material to material. However, these radiation spectra can be drastically altered by modifying the geometry of the structures. In particular, several approaches have been proposed to achieve narrowband, highly directional thermal emittance based on photonic crystals, gratings, textured metal surfaces, metamaterials, and shock waves propagating through a crystal. Here we present optimized aperiodic structures for use as narrowband, highly directional thermal infrared emitters for both TE and TM polarizations. One-dimensional layered structures without texturing are preferable to more complex two- and three-dimensional structures because of the relative ease and low cost of fabrication. These aperiodic multilayer structures designed with alternating layers of silicon and silica on top of a semi-infinite tungsten substrate exhibit extremely high emittance peaked around the wavelength at which the structures are optimized. Structures were designed by a genetic optimization algorithm coupled to a transfer matrix code which computed thermal emittance. First, we investigate the properties of the genetic-algorithm optimized aperiodic structures and compare them to a previously proposed resonant cavity design. Second, we investigate a structure optimized to operate at the Wien wavelength corresponding to a near-maximum operating temperature for the materials used in the aperiodic structure. Finally, we present a structure that exhibits nearly monochromatic and highly directional emittance for both TE and TM polarizations at the frequency of one of the molecular resonances of carbon monoxide (CO); hence, the design is suitable for a detector of CO via absorption spectroscopy.

9162-51, Session 14

Unusual thermal emission from a 3D metallic photonic crystal: quasi-equilibrium limit *(Invited Paper)*

Mei-Li Hsieh, National Chiao Tung Univ. (Taiwan); Rajeev V. Shenoi, Shawn-Yu Lin, Rensselaer Polytechnic Institute (United States)

We report the observation of unusual thermal radiation at elevated temperatures (T=400-900K) from a three-dimensional metallic photonic-crystal composite that includes a micro-cavity. Upon thermal excitation, its emissive power at selective wavelengths does not correlate with its absorptivity - a deviation from the postulate of Kirchhoff law at thermodynamic equilibrium. The ratio of its emissive power to that of a black body at nominally the same surface temperature also far exceeds one- a deviation from Planck's radiation law. The excitation of photon gas in the photonic-crystal composite beyond the equilibrium Bose-Einstein distribution is suggested as a possible explanation.

9162-52, Session 14

Tensilely strained germanium nanomembranes for direct-bandgap infrared light emission *(Invited Paper)*

Roberto Paiella, Cicek Boztug, Boston Univ. (United States); Jose Sanchez-Perez, University of Wisconsin - Madison (United States); Jian Yin, Boston Univ. (United States); Max G Lagally, University of Wisconsin - Madison (United States)

The development of practical light sources based on group-IV semiconductors is a major outstanding goal of optoelectronics research, as a way to enable the continued integration of electronic and photonic functionalities on a CMOS compatible platform. However, this goal is severely complicated by the indirect energy bandgap of silicon, germanium, and related alloys. A possible solution is provided by the ability of biaxial tensile strain in Ge to lower the conduction-band edge at the direct (Gamma) point relative to the L-valley minima, until at a strain of about 1.9% the fundamental bandgap becomes direct.

Here we show that, by virtue of their ultrasmall thicknesses, Ge nanomembranes under externally applied mechanical stress are capable of accommodating such relatively high strain levels (up to over 2%). With this approach, we have demonstrated strong strain-enhanced Ge photoluminescence accompanied by a large strain-induced red shift in emission wavelength. A theoretical model of the emission properties of tensilely strained Ge has also been developed and applied to the measured high-strain luminescence spectra, providing evidence of population inversion. Finally, mechanically flexible photonic-crystal cavities have been developed on these nanomembranes, and used to demonstrate particularly large (20?) strain-induced enhancements in radiative efficiency, together with the observation of luminescence signatures associated with band-edge cavity modes. These results are promising for the development of group-IV semiconductor lasers for the technologically important short-wave infrared spectral region.

9162-53, Session 15

Recent progress in photonic crystals and their applications *(Invited Paper)*

Susumu Noda, Kyoto Univ. (Japan)

In this conference, I will report on the recent progress in photonic crystals. The examples include (i) ultrahigh-Q nanocavities, (ii) all-Si Raman nanolasers, (iii) broad-area high-power coherent photonic-crystal lasers, (iv) thermal-emission control for environmental sensing and thermo-photovoltaic power generation system, and (v) on-demand 3D optical control. Such a broad-range of progress in photonic crystals indicates that photonic crystal research has now entered advanced phases towards realization of ultimate control of photons.

9162-54, Session 15

Multi-color nanowire photonic crystal laser pixels *(Invited Paper)*

Ganapathi S. Subramania, Jeremy B. Wright, Sheng Liu, George T. Wang, Qiming Li, Alexander Benz, Daniel D. Koleske, Ping Lu, Sandia National Labs. (United States); Huiwen Xu, Luke F. Lester, The Univ. of New Mexico (United States); Ting-Shan Luk, Igal Brener, Sandia National Labs. (United States)

Emerging applications such as solid-state lighting and display technologies require micro-scale vertically emitting lasers with controllable distinct lasing wavelengths and broad wavelength tunability arranged in desired geometrical patterns to form “super-pixels”. Conventional edge-emitting lasers and current surface-emitting lasers do not produce a viable solution as they require abrupt changes in semiconductor bandgaps or cavity length. Here, we successfully address these challenges by introducing a new paradigm that extends the laser tuning range additively by employing multiple monolithically grown gain sections each with a different emission center wavelength. Using broad gain-bandwidth III-nitride multiple quantum well (MQW) heterostructures and a novel top-down nanowire photonic crystal nanofabrication we obtain single-mode lasing in the blue-violet spectral region(Sci. Rep,3,2982(2013)). This has a remarkable 60 nm of tuning (or 16% of the nominal centre wavelength) that is determined purely by the photonic crystal geometry. This approach can be extended to cover the entire visible spectrum.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.

9162-55, Session 15

Active nanophotonics technology *(Invited Paper)*

Yeshaiahu Fainman, Univ. of California, San Diego (United States)

Achieving the most compact footprint for photonic components is an important factor in the design of integrated optical devices. Like most other photonic components, the minimum size for a laser is ultimately governed by ?0, the free space wavelength of the laser emission. As the size of a conventional dielectric semiconductor laser is decreased towards ?0, three effects adversely influence the lasing process. Firstly, the roundtrip path of the optical wave in the gain medium is shortened, secondly radiative losses are increased and finally the field confinement inside the resonator is reduced, resulting in less overlap of the optical mode with the gain medium. All of these effects serve to increase the lasing threshold, so that lasing cannot be achieved below a certain size limit. The ultimate challenge is to reduce the size of the laser resonator in all three dimensions.

We introduced a new family of 3-D nanolaser resonators, developed design and fabrication methodology as well as testing and characterization procedures. The example devices experimentally validate our approaches and demonstrated lasers action at room temperatures. We also demonstrated a new family of scalable plasmonic nanoresonators exploiting coaxial structures and used these nanolasers to demonstrate thresholdless operation. There are a number of very important research directions that are still in initial stages and will need to be investigated further in the future.

9162-56, Session 15

Nanopillars for new device functionality *(Invited Paper)*

Diana L. Huffaker, Univ. of California, Los Angeles (United States)

No Abstract Available

9162-71, Session PWed

Light self-trapping in an array of sub wavelength waveguides

Gregorio Mendoza González, Erwin A. Martí Panameño, Benemérita Univ. Autónoma de Puebla (Mexico)

Based in the numerical experiment techniques, we study the propagation dynamics of an optical beam in an one-dimensional array of parallel subwavelength waveguides, possessing Kerr nonlinearity. In our problem we consider the plane wave and monochromatic approximations. The numerics are based in Finite Difference Time Domain (FDTD) method. With a constant Kerr coefficient, and selecting the array parameters (diameter and separation of the waveguides) as well as the incident radiation properties (wavelength, field amplitude, etc.), we are able to observe the self-trapping of the light in one single waveguide. The radiation self-trapping can be observed for different incidence angles.

9162-72, Session PWed

Third-harmonic generation enhancement in polymer-dispersed liquid crystal grating

Surawut Wicharn, Prathan Buranasiri, King Mongkut’s Institute of Technology Ladkrabang (Thailand)

In this paper, the enhancement of third-harmonic generation in one-dimensional periodic grating structure with low-index contrast, which is produced by holographic illuminated liquid crystal droplets and called polymer-dispersed liquid crystal grating, with near-infrared pumping has been demonstrated. The observed enhancement process is theoretically explained and modeled with a multiple-scale perturbation analysis and split-step Fourier transform technique, respectively. We show that the third-harmonic generation has been enhanced by setting the fundamental frequency wavelength to the long-wavelength band-edge of the first photonic band-gap of this periodic structure and satisfying band-edge phase-matched condition. The numerical results show that a dramatic enhancement of the third-harmonic field is observed near the long-wavelength band-edge of the second photonic band-gap. Furthermore, the total energy output of third-harmonic field is more than the energy that produced by a phase-matched nonlinear crystal.

9162-73, Session PWed

Cooperative behavior of quantum emitters coupled to plasmonic waveguides near frequency cutoff

Ruzan Sokhoyan, Harry A. Atwater Jr., California Institute of Technology (United States)

Future quantum computing and communication systems are likely to exploit coherently coupled quantum emitters. In free space, dipole-dipole interactions between quantum emitters drastically diminish when the inter-emitter spacing is comparable to half a resonant wavelength. Coupling quantum emitters to plasmonic structures could dramatically increase their interaction range, due to the small mode volume characteristic to plasmonic fields. Within the framework of

quantum electrodynamics, we articulate here how coupling quantum dipole emitters to a plasmonic waveguide could enable observation of quantum cooperative effects, focusing on the emitter entanglement and collective decay. We consider a single-mode plasmonic rectangular waveguide with a dielectric core and metal cladding which is known to mimic behavior of an epsilon-near-zero metamaterial at the frequency cutoff [1]. Assuming different resonant frequencies of the quantum emitters we investigate how the inter-emitter interactions are varied when approaching the cutoff frequency of the fundamental plasmonic mode supported by the waveguide. We calculate Purcell factor, collective decay and coupling parameters as a function of the spatial position and resonant frequencies of the emitters. We show that coupling emitters to an ?-near-zero waveguide allows one to relax the constraint on precision positioning of emitters which is crucial for other solid state based entanglement generation schemes and extend the spatial scale at which the superradiance can be observed.

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9162-74, Session PWed

Gold nanoplates can serve as mirrors to enhance nanoparticle electrodynamics

Zijie Yan, Ying Bao, Uttam Manna, Raman Shah, Norbert F. Scherer, The Univ. of Chicago (United States)

Mirrors are ubiquitous components of modern optical experiments, where they define laser cavities, serve as essential elements for beam steering and beam shaping (e.g., spatial light modulators), and play key roles in light-emitting and harvesting devices. Chemically synthesized single-crystalline Au nanoplates have atomically flat surfaces over micron length scales, representing “perfect” mirrors to reflect (near-) infrared laser beams with negligible distortion. Here we show that such Au nanoplates can serve as transmissive mirrors that enhance optical detection and electrodynamic interactions. We demonstrate enhanced optical trapping and optical binding of Ag nanoparticles in interferometric optical traps created by the Au plate mirrors. Moreover, in dark-field microscopy, the Au nanoplates behave analogously to extraordinarily transmissive substrates that improve the imaging of Ag nanoparticles near a nanoplate surface by enhancing the scattering of light from nanoparticles that are in close proximity (~100 nm) to the Au nanoplate. Our results show that Au nanoplates can serve as unique platforms as active photonic materials for optical manipulation and for the investigation of plasmonic interactions between different metallic nanostructures.

9162-57, Session 16

Photonic gauge field induced by dynamic modulation *(Invited Paper)*

Shanhui Fan, Kejie Fang, Stanford Univ. (United States)

We discuss some of our recent works in seeking to create a photonic gauge field through dynamic modulation. We also review some of the progress in experimental demonstration of such a time-reversal-symmetry-breaking gauge field, including our own experimental work in the RF wavelength range, the electro-optic modulation work by Lipson at Cornell, and the acoustic-optic modulation work by Li and Eggleton at Sydney.

9162-58, Session 16

Nonlinear optical phononics: Inducing and harnessing stimulated Brillouin scattering in nanoscale photonic circuit waveguides *(Invited Paper)*

Benjamin J. Eggleton, The Univ. of Sydney (Australia)

We review recent progress in inducing and harnessing stimulated Brillouin scattering (SBS) in integrated photonic circuits. Exciting SBS in a chip-scale device is challenging due to the stringent requirements on materials and device geometry. We discuss these requirements, which include material parameters, such as optical refractive index and acoustic velocity, and device properties, such as acousto-optic confinement. Recent work on SBS in nano-photonic waveguides and micro-resonators is presented, with special attention paid to photonic integration of applications such as narrow-linewidth lasers, slow- and fast-light, microwave signal processing, Brillouin dynamic gratings, and nonreciprocal devices.

9162-59, Session 16

PT-symmetric synthetic materials and structures *(Invited Paper)*

Demetrios N. Christodoulides, Mohammad-Ali Miri, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

We provide an overview of recent developments in parity-time symmetric optical materials and structures. As it will be shown, PT-symmetry can be directly realized in optics through a judicious intermixing of optical gain, loss, and index guiding. The properties and possible optical functionalities that could emerge from this symmetry will be also discussed in this talk.

9162-60, Session 16

Single mode PT symmetric large area lasers

Hossein Hodaei, Mohammad-Ali Miri, Matthias Heinrich, Demetrios N. Christodoulides, Mercedeh Khajavikhan, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

In the last few years, compact high-power single-mode semiconductor lasers have been the focus of considerable attention for integrated photonic applications. Despite the intense activity in this area, the realization of such sources in a fully integrated fashion still remains a challenging task. Various strategies to preferentially encourage lasing in the fundamental mode have so far been suggested including spatial filtering by which one aims to increase the losses (or at least lower the gain) experienced by the undesirable modes, without unduly influencing the lasing threshold of the fundamental mode. However, the resulting laser devices tend to be significantly more sensitive to longitudinal and lateral perturbations.

Quite recently, a new approach has been proposed to resolve these issues by utilizing parity-time (PT) symmetry. When the refractive index of an optical arrangement is described by an even profile, while its gain/loss obeys an anti-symmetric distribution, the corresponding eigenvalue spectrum may be entirely real-valued. As a consequence, the modes experience zero net gain or loss, unless PT symmetry is spontaneously broken. Within the context of large-mode-area lasers, this phase transition can be judiciously tuned to present substantial gain to the fundamental mode, while appearing neutral to all the higher order modes. Here we demonstrate a novel class of large-area single-mode semiconductor distributed feedback lasers in which notions from parity-time symmetry is employed to reliably suppress higher-order

spatial modes while the DFB structure ensure single longitudinal mode operation. Our work provides an important step towards harnessing PT symmetry to enforce single-mode operation in intense large mode-area lasers.

9162-61, Session 16

Unidirectional lasing emerging from frozen light in nonreciprocal cavities *(Invited Paper)*

Hamidreza Ramezani, Univ. of California, Berkeley (United States); Tsampikos Kottos, Wesleyan Univ. (United States); Ilya Vitebskiy, Air Force Research Lab. (United States)

We introduce a class of unidirectional lasing modes associated with the frozen mode regime of nonreciprocal slow-wave structures. Such asymmetric modes can only exist in cavities with broken time-reversal and space inversion symmetries. Their lasing frequency coincides with a spectral stationary inflection point of the underlying passive structure and is virtually independent of its size. These unidirectional lasers can be indispensable components of photonic integrated circuitry.

9162-62, Session 17

Isotropic Dirac cones in the Brillouin-zone center of photonic crystals and metamaterials *(Invited Paper)*

Kazuaki Sakoda, National Institute for Materials Science (Japan) and Univ. of Tsukuba (Japan); Hiroyuki Takeda, National Institute for Materials Science (Japan)

The isotropic linear dispersion relation in the Brillouin zone of optical periodic structures, which is often called (photonic) Dirac cones, has been attracting considerable interest, since it can realize interesting optical phenomena such as unidirectional propagation of surface modes and optical simulation of Zitterbewegung. In particular, Huang et al. (Nature Mater., 2011) clarified that isotropic Dirac cones in the Brillouin-zone center can be created by accidental degeneracy of two modes for two-dimensional square- and triangular-lattice dielectric photonic crystals.

On the other hand, we showed by the tight-binding approximation for metamaterials characterized by well-defined electro¬magnetic resonant states localized in their unit structures that the particular combination of the symmetry of the two modes results in the Dirac cone (Opt. Express, Vol. 20, p.3898 (2012)) and the double Dirac cone (Opt. Express, Vol. 20, p.9925 (2012)). Later we extended this discussion to general cases by developing a degenerate perturbation theory for the vector electromagnetic field combined with the group theory (Opt. Express, Vol. 20, p.25181 (2012)) and proved the presence of the Dirac cones and double Dirac cones in the square, triangular, and cubic systems.

In this presentation, we extend our calculation to photonic crystals and metamaterials of different spatial symmetries and examine the method to realize and detect Dirac cones in optical frequencies. In particular, we discuss the possibility of their creation in photonic crystal slabs by numerical examination of their dispersion relation.

9162-63, Session 17

Photonic analog of graphene: novel functions inspired by condensed matter physics *(Invited Paper)*

Tetsuyuki Ochiai, National Institute for Materials Science (Japan)

Conical dispersion in 2d and 3d physical systems attracts growing interests recently.

Graphene, monolayer of Carbon atoms arranged in a honeycomb lattice, is a typical example that exhibits the so-called Dirac cone around the Brillouin zone corners. Honeycomb-lattice photonic crystals (PhCs) composed of parallel cylinders also exhibit the Dirac cone whose mass gap is controllable with the symmetry of the structures.

We thus refer to the honeycomb-lattice PhCs as photonic analog of graphene.

The controllability enables us to design various novel light transports in the bulk, edge, and interface, inspired by notions developed in condensed-matter physics.

I will present fundamental properties of the photonic graphene and their possible applications.

9162-64, Session 18

Nonlinear evolution of slow light pulses *(Invited Paper)*

Kobus Kuipers, FOM Institute for Atomic and Molecular Physics (Netherlands)

One of the advantages of slow light in photonic crystals is that the slowdown of the light propagation enhances nonlinear processes. Investigation of these processes is however far from trivial. As is always the case in nonlinear optics, the sequence of components in a device matters to the overall nonlinear response of the composite device. As a consequence it is hard from input-output measurements to determine how each individual component contributes to the overall evolution of slow light pulses. In order to solve this we demonstrate, following the electrical analogue, nanoscale photonic point-to-point measurements characterizing a single component inside a composite device. We perform spectrally resolved near-field scanning optical microscopy on ultrashort pulses propagating inside a slow light photonic crystal waveguide, which is part of a composite sample. A power study reveals a reshaping of the pulse's spectral density, which we model using the nonlinear Schrödinger equation. With the model, we are able to identify the various physical processes governing the nonlinear pulse propagation. Finally, we contrast the near-field measurements with transmission measurements of the complete composite sample to elucidate the importance of gaining local information about the evolution of the spectral density.

9162-65, Session 18

Slow-light metawaveguides

Stavroula Foteinopoulou, Univ. of Exeter (United Kingdom)

We demonstrate the strong coupling between backward and forward guided modes in a left-handed material(LHM)-right-handed material (RHM) heterostructure waveguide leading to a slow light mode that can extended over a wide modal-index bandwidth. Our dynamic simulations in time-domain reveal that the latter is a most crucial feature for effectively achieving ultra-slow propagation of EM energy. We further show with our paradigm that strong temporal compression leads to a mesoscopic intensity enhancement, covering areas of the order of the free space wavelength without the need for a strong spatial compression.

9162-66, Session 18

Optically induced indirect photonic transitions in a slow light photonic crystal waveguide *(Invited Paper)*

Manfred Eich, Michel Castellanos Munoz, Alexander Y. Petrov, Technische Univ. Hamburg-Harburg (Germany); Liam O'Faolain, Univ. of St. Andrews (United Kingdom); Juntao Li, Univ. of St. Andrews (United Kingdom) and Sun Yat-Sen Univ. (China);

Thomas F. Krauss, Univ. of St. Andrews (United Kingdom) and The Univ. of York (United Kingdom)

The presentation will cover our work on indirect photonic transitions in a silicon slow light photonic crystal waveguide. The transitions are driven by an optically generated refractive index front that moves along the waveguide and interacts with a signal pulse copropagating in the structure. The structure described is genuinely nonreciprocal, as it provides different frequency shifts for co- and counterpropagating signal and index fronts.

9162-67, Session 18

Theory and experimental demonstration of enhanced gain in slow light photonic crystal waveguides *(Invited Paper)*

Jesper Mørk, Yaohui Chen, Per Lunnemann Hansen, Sara Ek, Elizavetta S. Semenova, Kresten Yvind, Technical Univ. of Denmark (Denmark)

In this talk we experimentally demonstrate that by the use of slow light effects, the gain coefficient of a semiconductor waveguide can be enhanced beyond the value given by the material gain. The device investigated is a photonic crystal membrane structure with embedded layers of quantum wells or quantum dots. Furtermore, an effective model in terms of propagating Bloch waves is derived and fundamental limitations to the gain enhancement are discussed.

9162-76, Session 18

True stopping of light: a new regime for nanophotonics *(Invited Paper)*

Kosmas L. Tsakmakidis, Xiang Zhang, Univ. of California, Berkeley (United States); Ortwin Hess, Imperial College London (United Kingdom)

The extremely large speed of light is a tremendous asset but also makes it challenging to control, store or shrink beyond its wavelength. Particularly, reducing the speed of light down to zero is of fundamental scientific interest that could usher in a host of important photonic applications, some of which are hitherto fundamentally inaccessible. These include cavity-free, low-threshold nanolasers, novel solar-cell designs for efficient harvesting of light, nanoscale quantum information processing (owing to the enhanced density of states), as well as enhanced biomolecular sensing. We shall here present nanoplasmonic-based schemes where time-dependent sources excite “complex-frequency” modes in uniform (plasmonic) heterostructures, enabling complete and dispersion-free stopping of light pulses, resilient to realistic levels of dissipative, radiative and surface-roughness losses. Our theoretical and computational results demonstrate extraordinary large light-deceleration factors (of the order of 15,000,000) in integrated nanophotonic media, comparable only to those attainable with ultracold atomic vapours or with quantum coherence effects, such as coherent population oscillations, in ruby crystals.

9162-68, Session 19

Generation and control of vortex beams using twisted nonlinear photonic crystals *(Invited Paper)*

Ady Arie, Tel Aviv Univ. (Israel)

Twisted nonlinear photonic crystals can be realized by introducing an edge dislocation into an otherwise periodically poled quadratic nonlinear crystal. In this case, the second order nonlinear coefficient has a fork-shaped form. By sending a pump beam transversely to the plane of the dislocation, a vortex beam is generated at the second harmonic, whose orbital angular momentum is determined by the crystal. Furthermore, when the pump beam travels longitudinally, in the plane of the dislocation, the parity of the dislocation’s topological charge governs the transfer of energy between an input wave and its second harmonic.

9162-69, Session 19

The topological photonic states in gyrotropic microstructured materials *(Invited Paper)*

Yanfeng Chen, Minghui Lu, Cheng He, Nanjing Univ. (China)

The topology of electronic systems has recently attracted much attention in condensed matter physics research because of its unique properties including robust unidirectional chiral edge (surface) states and fermionic time-reversal symmetry protected momentum-dependent spin polarization of such edge (surface) states in quantum spin Hall (topological insulator) system. In this talk, we propose some quasi-particle counterparts of the quantum spin Hall effect (topological insulator) in two-dimensional photonic or phononic crystals. For photonic analogy, two linear electromagnetic polarizations (transverse electric and transverse magnetic waves) can propagate in one-way with opposite directions at the edge of photonic crystal composed of a gyrotropic medium exhibiting both gyroelectric and gyromagnetic properties simultaneously. Two circular polarizations (left-circular and right-circular waves) can be used to realize photonic topological insulator by piezo-electric and piezo-magnetic superlattices as well. Such photonic topological systems show unidirectional polarization-dependent transportation of photonic topological edged states, which is robust against certain disorders and impurities. Analyzing the symmetry in these systems, we find that some bosonic time-reversal invariant chiral impurities would invalidate such topological states, indicating that the conventional bosonic time-reversal symmetry is not valid to protect their robustness. Instead, the robustness is rather protected by a new symmetry, which might be the general requirement for topological photonic crystals. Thus, we find that this unique property is not protected by conventional time-reversal symmetry of photons obeying the bosonic statistics with T2=1 but rather by the same symmetry, T2=-1, as electron’s time-reversal symmetry. Based on the tight-binding approximation approach, we construct an effective Hamiltonian for these photonic structures, which have a similar form to that of an electronic system. Furthermore, the Z2 invariant of such models is calculated in order to unify their topological non-trivial character. Our finding provides a viable way to exploit the topological property of quasi-particles, and also can be used to develop a platform to mimic the spin properties of electrons.

9162-70, Session 19

Topological feature in silicon photonics *(Invited Paper)*

Mohammad Hafezi, Joint Quantum Institute (United States)

We investigate the effect of synthetic gauge fields on various photonic transport properties. In particular, we demonstrate the robustness of topological edge states in a photonic system of coupled microring resonators. Using direct imaging and transmission analysis, we show that the edge states are less susceptible to lattice disorders than bulk states.

9163-1, Session 1

Bringing metamaterials to real applications *(Invited Paper)*

Vladimir M. Shalaev, Alexander V. Kildishev, Alexandra Boltasseva, Purdue Univ. (United States)

Basic requirements and challenges for brining metamaterials (MMs) to real-life applications will be discussed. We also review the recent progress in developing tunable and active MMs, nanolasers, and a new means for engineering the photonic density of states with MMs. Novel plasmonic materials with superior properties based on transparent conducting oxides and ceramics will be outlined. Finally, we consider a new approach for controlling light by using 2D meta-surfaces.

9163-2, Session 1

Graphene plasmonics and nanophotonics *(Invited Paper)*

Harry A. Atwater Jr., California Institute of Technology (United States)

Field effect tuning of the electrochemical potential in graphene nanoresonators enables the plasmon and phonon dispersion to be measured. We experimentally demonstrate a method of efficiently coupling long-wavelength freespace light into nanoscale graphene plasmonic resonators. Despite the large wavelength mismatch and the thinness of the graphene sheet, we show that nearly 25% of incident radiation at 7.2 microns can be coupled into 40nm graphene nanoresonators - an order of magnitude improvement over conventional silicon dioxide/Si-based graphene devices. This large enhancement of absorption is achieved by employing a “Salisbury screen”-type geometry, where a back reflector is held in the vicinity of the graphene nanoresonators to create a destructive interference effect. Our calculations show that this simple geometry allows for the impedance of the graphene plasmonic modes to be matched to the freespace impedance, which results in the efficient absorption that we observe. We can further tune the metasurface impedance to modulate this effect, either by electrostatically varying the carrier density in situ, or by patterning the graphene nanoresonators to different lengthscales. Those controls allow us to electronically tune the absorption from 0 to 25%, and demonstrate at least 22% absorption over 100cm-1 of bandwidth.

9163-3, Session 2

Topological insulator for broadband switchable metamaterials *(Invited Paper)*

Jun-Yu Ou, Jin-Kyu So, Univ. of Southampton (United Kingdom); Giorgio Adamo, Zilong Wang, Jun Yin, Venkatram Nalla, Stefano Vezzoli, Azat Sulaev, Lan Wang, Handong Sun, Cesare Soci, Nanyang Technological Univ. (Singapore); Nikolay I. Zheludev, Optoelectronics Research Ctr. (United Kingdom) and Nanyang Technological Univ. (Singapore)

Topological Insulator BiSbTeSe (BSTS) is introduced as a broadband plasmonic material ranging from mid-IR to UV. Dielectric constants derived from ellipsometric measurements are in excellent agreement with first principle DFT calculations showing two regions of anomalous dispersion due to the combination of bulk interband transitions and surface contribution of the topologically protected states in the UV and the bandgap region (~5 ?m). Metamaterials and gratings are fabricated on the BSTS crystal showing strong plasmonic response from UV to NIR. This, combined with ultrafast (t>100 fs) modulation of its optical response, shows the potential of Topological Insulators as platforms for high-frequency switchable metamaterials.

9163-4, Session 2

Yttrium hydride nanoantennas for active plasmonics

Nikolai Strohfeldt, Andreas Tittl, Martin Schäferling, Frank F. Neubrech, Univ. Stuttgart (Germany); Uwe Kreibig, RWTH Aachen (Germany); Ronald Griessen, Vrije Univ. Amsterdam (Netherlands); Harald W. Giessen, Univ. Stuttgart (Germany)

A key challenge for the development of active plasmonic nanodevices is the lack of materials with fully controllable plasmonic properties. In this work, we demonstrate that a plasmonic resonance in top-down nanofabricated yttrium antennas can be completely and reversibly turned on and off using hydrogen exposure. We fabricate arrays of yttrium nanorods and optically observe in extinction spectra the hydrogen-induced phase transition between the metallic yttrium dihydride and the insulating trihydride. Whereas the yttrium dihydride nanostructures exhibit a pronounced particle plasmon resonance, the transition to yttrium trihydride leads to a complete vanishing of the resonant behavior. The plasmonic resonance in the dihydride state can be tuned over a wide wavelength range by simply varying the size of the nanostructures. By modifying the dielectric function of yttrium dihydride from literature to include nanofabrication-specific effects, we are also able to perfectly reproduce our experimental extinction spectra in numerical simulations, what allows us to make quantitative predictions about the resonance width and position of any yttrium-based plasmonic nanodevice. Furthermore, we develop an analytical diffusion model to explain the temporal behavior of the hydrogen loading and unloading trajectories observed in our experiments and gain information about the thermodynamics of our device. Thus, our nanorod system serves as a versatile basic building block for active plasmonic devices ranging from switchable perfect absorbers to active local heating control elements.

9163-5, Session 2

Electrodynamic description of spasers: multipolar modes, universal figures of merit, and minimal gain threshold

Nikita Arnold, Calin Hrelescu, Thomas A. Klar, Johannes Kepler Univ. Linz (Austria)

Although a spaser is in principle a quantum-mechanical system, we demonstrate that it can be conveniently described within a purely electrodynamic framework. Both spasing threshold and post-threshold operation are in some respect conceptually similar to a conventional laser, where an electrodynamic framework can also be applied as long as gain saturation is included in the dielectric constant close to and beyond threshold.

We find universal expressions for the necessary threshold-gain for small (unretarded) particles of arbitrary shape. The minimal required gain at a specific wavelength depends only on the optical materials constants of the metal and the gain matrix, and is independent of the particle shapes. With realistic non-restrictive assumptions about the gain medium, this wavelength is close to the spectral minimum of the ratio -Im(eps_met)/Re(eps_met) , which therefore represents the universal figure of merit for a given metal. When Ag is used as a metal and a typical polymer as a host matrix, spasing can be expected at -Im(eps_gain)=0.026, which corresponds to a realistic dye concentration of some 10^19 cm^3.

Nevertheless, once the minimally necessary gain at a specific frequency

is determined via the materials constants, the specific geometric parameters, such as aspect ratios of rods or shells can be determined which allow for spaser operation at this minimal gain.

These general considerations are illustrated with two examples: (i) retarded calculations for dipolar modes of finite sized silver rods and (ii) semi-analytical simulations for spherical shells, both submerged in gain medium.

9163-6, Session 2

Active plasmonic devices *(Invited Paper)*

Uriel Levy, Liron Stern, Boris Desiatov, Meir Grajower, Alexandros Emboras, The Hebrew Univ. of Jerusalem (Israel)

In this talk we demonstrate the role of metal optics in enhancing the performances of active devices. This includes the demonstrations of various concepts and devices ranging from plasmonic enhanced silicon Schottky detectors for the near IR, resistive memory devices based on the platform of silicon plasmonics. Finally, we will demonstrate our recent results related to a coupled plasmonic-atomic system which provides the capability of controlling the resonant lineshape at will.

9163-7, Session 2

Plasmonic black metal polarizers for ultra-short laser pulses

Thomas M. Sondergaard, Esben Skovsen, Aalborg Univ. (Denmark); Christoph Lemke, Christian-Albrechts-Univ. zu Kiel (Germany); Tobias Holmgaard, Mekoprint A/S (Denmark); Till Leißner, Christian-Albrechts-Univ. zu Kiel (Germany); René L. Eriksen, Jonas Beermann, Univ. of Southern Denmark (Denmark); Michael K. Bauer, Christian-Albrechts-Univ. zu Kiel (Germany); Kjeld Pedersen, Aalborg Univ. (Denmark); Sergey I. Bozhevolnyi, Univ. of Southern Denmark (Denmark)

This paper considers theoretically and experimentally a range of plasmonic-black-metal polarizers suitable for ultra-short pulses. The polarizers consist of a metal surface being nanostructured with a periodic array of ultra-sharp grooves with periods of 250-350 nanometers, and groove depths around 500 nanometers. The surfaces can be designed such that practically all incident light with electric field perpendicular to the groove direction is absorbed. The efficient absorption is due to incident light being coupled into gap-plasmon polaritons that propagate downwards in the gaps between groove walls towards the groove bottom, where it is then subsequently absorbed during propagation. Reflection is largely avoided due to an adiabatic groove taper design. The other polarization, however, is very efficiently reflected, and the main point of this paper is that the reflection is (both theory and experiments) with negligible dispersive stretching even for ultra-short pulses of 5-10 femtoseconds temporal width in the visible and near-infrared. For comparison pulse propagation through 1-mm silica glass can cause a pulse to increase from 5 femtoseconds to more than 20 femtoseconds. Temporal pulse shapes after reflection are calculated by decomposing the incident laser pulse into temporal Fourier components, calculating the reflection coefficient in the frequency domain, and then Fourier-transforming the reflected pulse back to the time-domain. Reflection of pulses is compared for polarizers based on different metals (gold, nickel, chromium) with a range of groove-array designs and directions of light incidence, a range of center wavelengths and pulse widths for the incident pulse.

9163-8, Session 3

Giant nonlinear response from plasmonic metasurfaces coupled to intersubband transitions *(Invited Paper)*

J. Lee, M. Tymchenko, Christos Argyropoulos, Pengyuan Chen, Feng Lu, The Univ. of Texas at Austin (United States); Frederic Demmerle, Gerhard Böhm, Markus-Christian Amann, Walter Schottky Institut (Germany); Andrea Alu, Mikhail A. Belkin, The Univ. of Texas at Austin (United States)

Ultrathin metamaterials with giant nonlinear optical response may enable applications including super-resolution imaging, efficient frequency conversion and optical control with greatly-relaxed phase-matching conditions, as well as for optical switching and memories at the nanoscale. Current efforts to enable giant nonlinear response in metamaterials were focused mostly on using the natural nonlinear response of plasmonic metals or by enhancing the nonlinearity of optical crystals using plasmonic nanoantennas. These approaches failed, however, to create structures with nonlinear response many orders of magnitude higher than that of bulk nonlinear materials.

In this work, we demonstrate that by coupling of a quantum-engineered multi-quantum-well semiconductor layer with electromagnetically-engineered plasmonic elements we may produce ultrathin planarized metasurfaces with giant nonlinear response. Our approach allows creating large-area metasurfaces in which virtually any element of the effective nonlinear susceptibility tensor may be engineered.

We experimentally prove the concept by designing and fabricating 400-nm-thick metasurfaces for second harmonic generation at lambda~8um. The effective nonlinear susceptibility over 50 nm/V was measured for second-harmonic generation under normal incidence, which is 3-4 orders of magnitude larger than that provided by traditional nonlinear crystals or nonlinear metasurfaces reported to date. The practical impact of the nonlinear metasurfaces proposed here may be extended to a variety of fields, including THz generation and detection, phase conjugation, and other nonlinear processes.

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9163-9, Session 3

High accuracy models of sources in FDTD computations for subwavelength photonics design simulations

James B. Cole, Univ. of Tsukuba (Japan); Saswatee Banerjee, Sumitomo Chemicals Co., Ltd (Japan)

The finite difference time domain (FDTD) algorithm is popular tool for photonics design, but the error of conventional second-order FDTD is about h**2/12, where h is the grid spacing, and the errors due to the source model further increase it. Even with supercomputers many practical design problems are too large to solve. Nonstandard (NS) FDTD, based on a superposition of second-order finite differences, has been demonstrated to give much higher accuracy than conventional FDTD for the sourceless wave equation and Maxwell's equations (h**6 / 24192).

We can analytically compute the field due to a point source in an unbounded homogeneous medium. This analytical solution is inserted into the NS finite difference (FD) model and the parameters of the source model are adjusted so that the FDTD solution very nearly matches the analytical one. To derive the scattered field source model, we use the NS-FD model of the total field and of the incident field to deduce the correct source model.

Sources that generate a scattered field must be modeled differently from ones radiate into free space. We demonstrate the high accuracy of our source models by comparing with analytical solutions. This approach yields a significant improvement inaccuracy, especially for the scattered field, where we verified the results against Mie theory. The computation time and memory requirements are about the same as for conventional FDTD.

We apply these developments to model such sources as quantum dots in optical circuits and systems, and to solve design and propagation problems in subwavelength structures.

9163-10, Session 3

Plasmonic nanoparticle strings: threading nanoparticle chains with light *(Invited Paper)*

Lars O. Herrmann, Ventsislav K. Valev, Univ. of Cambridge (United Kingdom); Christos Tserkezis, Centro de Fisica de Materiales (Spain); Jonathan S. Barnard, Univ. of Cambridge (United Kingdom); Setu Kasera, Melville Lab. for Polymer Synthesis (United Kingdom); Oren A. Scherman, Univ. of Cambridge (United Kingdom); Javier Aizpurua, Centro de Fisica de Materiales (Spain); Jeremy J. Baumberg, Univ. of Cambridge (United Kingdom)

Light-matter interactions in the nanoscale can be efficiently controlled by novel plasmonic materials. One particularly attractive approach to fabricate and tailor such nanomaterials is by using light itself. Here we demonstrate an efficient way to exploit light for threading plasmonic nanoparticle strings, that is, creating chains of gold nanospheres conductively connected via gold threads with well-controlled dimensions. Gold nanosphere clusters are first self-assembled with use of appropriate rigid organic molecular linkers, namely cucurbiturils, which fix the interparticle gaps at precisely 0.9 nm. In such self-assemblies the excitation of collective plasmonic modes (called Capacitive Chain Plasmons, CCP) along linear and quasi-linear nanoparticle chains within the clusters leads to long-wavelength extinction resonances, accompanied by huge near-field enhancement at the interparticle gaps. The near-field enhancement is then exploited for threading, which is achieved by illuminating with ultrafast lasers whose wavelength coincides with that of the CCP mode, thus enabling non-thermal melting of gold at the gaps. This formation of plasmonic threads allows charge transfer within the entire nanoparticle strings, leading to the appearance of new, hybrid chain/rod modes in the infrared, called Threaded Chain Plasmons (TCP). The evolution and optical properties of the TCP modes, and their dependence on string length and thread width are analysed both experimentally and theoretically. Finally, we show that the nanoparticle size, chain length, and laser power offer unique control of the thread widths, which can be identified with a precision significantly exceeding that of electron microscopy by comparing experimental and simulated extinction spectra.

9163-11, Session 4

Graphene as a platform for dynamically controlled plasmonics *(Invited Paper)*

Alexandra Boltasseva, Naresh K. Emani, Ting-Fung Chung, Alexander V. Kildishev, Yong P. Chen, Vladimir M. Shalaev, Purdue Univ. (United States)

Graphene exhibits several remarkable optical properties like large optical transparency, saturable absorption and broadband nonlinear response which can have wide ranging applications in light harvesting and detection, touchscreens and ultrafast lasers. The main challenge in translating this remarkable potential to real applications is enhancing the interaction of light with graphene. Graphene being a single layer of carbon atoms absorbs only 2.3% of incident radiation. This can be enhanced by integrating plasmonic nanostructures in the vicinity of graphene, and also by patterning graphene leading to excitation of its intrinsic plasmons. The intrinsic plasmons in graphene are not efficient in confining light below 6 μm wavelength due to rapid decay by optical phonons. In this talk we focus on graphene antenna hybrid devices and specifically on controlling the optical properties of plasmonic structures operating at near-IR and mid-IR frequencies with graphene. The optical properties of graphene exhibit strong dependence on the sheet carrier density which can be dynamically controlled by a gate voltage. Therefore when plasmonic antennas are fabricated on top of graphene, their optical properties can be tuned by modulating charge density in underlying graphene. Dynamic modulation in bow-tie and Fano resonant plasmonic antennas will be presented. Additionally, need for novel doping techniques like ion-gel gating and reduction in work function mismatch between antennas and graphene will be discussed. Finally the current prospects and future directions for improvements will be identified

9163-12, Session 4

Mid-infrared nanosplasmonics on graphene: broadband antennas, detectors, and modulators *(Invited Paper)*

Federico Capasso, Harvard School of Engineering and Applied Sciences (United States)

By incorporating suitable MIM structures in optical antenna designs, we demonstrate an electrically tunable coupled antenna array on graphene with a large tuning range (1100 nm, i.e. 250 cm-1, nearly 20% of the resonance frequency) of the antenna resonance at mid-ir wavelengths (6-7 μm), almost twice the bandwidth than previously reported using gratings of linear coupled Au optical antennas on graphene. Using doubly-resonant antenna arrays, mid-ir intensity modulation has been demonstrated with maximum modulation depth of more than 30% and a bandwidth of 600 nm. Much higher on-off ratio can be achieved by designing a critically coupled structure. Our devices exhibit a 3dB cut-off frequency of 30 MHz, which can be further increased into the GHz range.

Applications to graphene detectors so far are still limited by low responsivity due to the weak optical absorption (only 2.3% in the monolayer graphene sheet) and short photo-carrier lifetime (< 1 ps). We will report on an investigation of closely-coupled metallic antenna structures on graphene and show that they can be utilized to simultaneously improve both the light absorption and photo-carrier collection. We have demonstrated room temperature mid-infrared (mid-IR) antenna-assisted graphene detectors with more than 200 times enhancement of responsivity (~0.4 V/W) compared to devices without antennas (<2 mV/W).

9163-13, Session 4

Deep modulation of mid-infrared light using plasmonic fano-resonant meta-surfaces integrated with graphene *(Invited Paper)*

Gennady B. Shvets, The Univ. of Texas at Austin (United States)

Plasmonic metasurfaces enhance light-matter interaction by focusing light into extremely subwavelength dimensions. These carefully designed structures have been used in extremely thin optical component which can mold the wavefront, with exciting applications in optical lenses, beam steering, and biosensing applications. Adding dynamic tunability to these devices opens up the possibility for new application in single pixel detection and 3D imaging as well as optical modulators and switches. However the existing approaches for designing active optical devices in infrared, are either slow or have small refractive index change. Plasmonic antennas integrated with single-layer graphene (SLG) was recently utilized for high-speed modulation, but with modest modulation depth (MD). In this work, we take advantage of SLG integration with Fano-resonant metasurface to achieve an order of magnitude MD.

We made two samples with two different gap sizes (Sample 1: G=70nm, Sample 2: G=100nm). The free carrier density N is proportional to ΔV=V_g-V_CNP which is the gate voltage relative to the charge neutrality point voltage. The modulation depth (MD) defined as MD(N=x,λ)=R(N=0,λ)/(R(N=x,λ)) for these two samples was

experimentally measured to reach 500 % and 1000 % for Samples 1 and 2 respectively at around λ≈7μm as N increases from zero to N=4.8e12 (cm)^(-2). Our simulation indicate that reflection phase changes by about 90 degrees at λ≈7.2μm as N varies between 1.6e12< N<4.8e12 (cm)^(-2).

In conclusion, we demonstrate that graphene integration with a Fano-resonant metasurface is a promising platform for strong modulation of amplitude and phase of infrared light. The high modulation rate of graphene charge carriers promises the next generation of high-speed modulators and beam steering photonic platforms.

This work is supported by the Office of Naval Research (ONR) through the grant N00014-13-1-0837

9163-14, Session 4

Exciton-plasmon interactions in graphene-semiconductor structures *(Invited Paper)*

Tigran V. Shahbazyan, Jackson State Univ. (United States); Kirill A. Velizhanin, Los Alamos National Lab. (United States)

Doped monolayer graphene with Fermi energy in the range 0.2-0.6 eV exhibits a stable in-plane plasmon wave in the infrared frequency range with gate-tunable wavelength well the below radiation wavelength at the same frequency. A large local density of states of graphene plasmons as compared to that of surface plasmon polaritons on metal surfaces ensures a very efficient graphene plasmon coupling to excitons in semiconductor nanostructures such as quantum dots (QD) and quantum wells (QW) situated at a close distance to the graphene sheet. We present our recent results on both weak and strong coupling between plasmons and excitons in graphene-semiconductor structures. In the former case, we discuss highly efficient long-range energy transfer between excitons in QDs mediated by graphene plasmons over distances far exceeding the Forster radius. In the latter case, we discuss excitations in narrow gap semiconductor QW separated from graphene by a potential barrier and show that Coulomb interactions between QW excitons and graphene plasmons lead to mixed states characterized by Rabi splitting of about 100 meV for small graphene-QW separations.

9163-15, Session 4

Plasmons in inhomogeneously doped graphene nanostructures

Iván Silveiro, Francisco Javier García de Abajo, ICFO - Institut de Ciències Fotòniques (Spain)

Doped graphene has emerged as a promising plasmonic material at THz and IR frequencies due to its peculiar electronic band structure. The plasmonic response of this material has been generally studied under a uniform doping configuration. However, realistic geometrical configurations produce inhomogeneities in the doping charge distribution. We study the effect of inhomogeneous doping in extended graphene, as well as in nanodisks and ribbons. For a periodically doped graphene sheet we predict 100% light absorption [1], which is accompanied by high levels of enhancement of the energy-transfer rate between an optical emitter and the graphene sheet [2]. We also study plasmons in graphene nanodisks including the effect of inhomogeneity in the distribution of the doping charge. Specifically, we discuss the following two configurations: charged disks containing a fixed amount of additional carriers, which are self-consistently distributed along its surface to produce a uniform voltage; and neutral disks exposed to a neighboring external point charge. For charged disks, we find dipolar plasmons similar to those of uniformly doped graphene structures, with the plasmon induced charge piling up near the edges [3]. In contrast, neutral disks exhibit a p-n junction at a certain distance from the disk center, giving rise to plasmon modes that are strongly localized at that particular radius. We further illustrate how axially symmetric graphene dark-plasmons can be excited by coupling to a neighboring metallic element. Our results provide an in-depth understanding of graphene behavior under these doping conditions.

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9163-16, Session 5

The spasing and loss compensation in plasmonic nanoshell laser *(Invited Paper)*

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We here presents the first unified theory of the response of plasmonic nanoshells assisted by optical gain media. Our approach combines rigorous Mie scattering equations for the plasmonic structure and the density matrix formalism, which is well known in laser physics, allowing a correct description of different relaxation and energy exchange channels in the system. We derive a fundamental equation for calculation of SPASER frequency which we claim to be valid for any type of SPASER physical geometry. We demonstrate that ONLY radiative losses are responsible for the spasing and loss compensation process in the laser resonator.

9163-17, Session 5

Plasmonic nanowire sensors and lasers *(Invited Paper)*

Limin Tong, Guo Xia, Xiaoqin Wu, Yipei Wang, Zhejiang Univ. (China)

No Abstract Available

9163-18, Session 5

Plasmonic waveguide filter based on metal-insulator-metal structure and its slow light effects

Jicheng Wang, Lin Sun, Yueke Wang, Jiangnan Univ. (China)

The plasmonic waveguides optical selective filters with double-groove shaped metal-insulator-metal(MIM) structure is proposed in theory. It was found that the transmission characteristics of such structures depend on the phase relationship between the plasmonic wave passing through the groove and the one returning to the waveguide from the groove, which can be interpreted by the interference theory. The simulation shows that transmission characteristics in the surface plasmon waveguide are changed as width of the double-groove increasing. In addition, we can find the phenomenon of slow light when the light passes through this structure.

9163-19, Session 5

Lossless surface plasmon polariton guiding in electrically driven nanowaveguides

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Physics and Technology (Russian Federation); Anatoly V. Zayats, King's College London (United Kingdom)

Implementation of optical components in microprocessors can boost their performance by orders of magnitude. However, the size of optical elements is fundamentally limited by diffraction, while miniaturization is one of the essential concepts in the development of high-speed and energy-efficient electronic chips. Surface plasmon polaritons (SPP) could be an efficient solution of this problem offering a unique opportunity to localize energy and guide signals at the nanoscale, but ohmic losses in the metal limit the SPP propagation length to a few tens of micrometers and suppress utilization of plasmonic waveguides in semiconductor chips. Realization of compact and energy-efficient loss compensation scheme eliminates this drawback, allowing the implementation of the plasmonic approach into numerous applications.

Recently, full loss compensation has been experimentally demonstrated with optical pumping, but low efficiency, operation only in the pulse regime and inability to integrate it on a chip makes electric pumping much more favourable.

In this work, we propose a novel SPP amplification scheme based on an Au/InAsP/InGaAs/AlInAs double-heterostructure tunneling Schottky-barrier diode in a waveguiding geometry with deep-subwavelength mode confinement.

The proposed scheme is shown to fully compensate SPP propagation loss at a moderate current density of about 20kA/cm2 in a steady-state regime under room-temperature conditions. Furthermore, the threshold current is reduced by one order of magnitude, as the temperature decreases down to 150K. The estimated power consumption of interconnects based on the proposed active waveguides is comparable with silicon photonics, which creates the backbone for the implementation of plasmonic components in on-chip circuits.

9163-20, Session 6

Isotropic infrared metamaterials *(Invited Paper)*

Takuo Tanaka, RIKEN (Japan); Atsushi Ishikawa, Okayama Univ. (Japan); Che-Chin Chen, Instrument Technology Research Ctr. (Taiwan); Din Ping Tsai, National Taiwan Univ. (Taiwan)

An isotropic infrared (IR) metamaterial consisting of three-dimensional (3D) metallic nanostructures is experimentally demonstrated by a newly-developed metal-stress driven self-folding method. Metamaterials have introduced a new paradigm over the last decade to create unprecedented optical functionalities using sub-wavelength resonant structures, i.e. meta-atoms. Since meta-atom is an analog of antenna that asymmetrically interacts with light, the resultant optical responses of metamaterials are inevitably anisotropic, severely limiting their practical applications. Isotropic responses of metamaterials have been achieved at microwave frequencies by employing 3D symmetric alignment of meta-atoms, but their optical versions are still elusive due to the challenge of 3D nanofabrication. Here, we present the first experimental realization of an isotropic IR metamaterial using fourfold-symmetric 3D configuration of metallic nanostructures. Mass-productive formation of the assembled 3D stereostructures was achieved by a metal-stress driven self-folding method. Systematic transmission spectroscopy demonstrated unambiguous isotropic characteristics for any lateral rotation, polarization, and incident angle up to 40º. The corresponding numerical simulations well re-produced the experimental results, revealing that the interplay of electric and magnetic interactions of the 3D meta-atom plays a crucial role for the bi-anisotropic responses. Our results demonstrated a promising method to manufacture highly symmetric metamaterials, leading to isotropic optical responses. We anticipate our technique to be a breakthrough for introducing the concepts of metamaterials to real-components, especially at optical frequencies.

9163-22, Session 6

Three-dimensional metamaterials: from split ring resonator to toroidal metamolecule *(Invited Paper)*

Yao-Wei Huang, Wei Ting Chen, Pin Chieh Wu, Chun Yen Liao, National Taiwan Univ. (Taiwan); Vassili A. Fedotov, Vassili Savinov, Nikolay I. Zheludev, Univ. of Southampton (United Kingdom); Din Ping Tsai, National Taiwan Univ. (Taiwan)

Split ring resonator (SRR) has attracted wide attentions since the discovery of negative refraction in 2002. In 2010, the toroidal resonance, a fundamental resonance mode that differ from electric or magnetic multi-dipole expansion, has found with the higher quality factor in its spectral response in compared to that of magnetic dipole resonance in microwave region. In this paper, we experimentally designed and fabricated three-dimensional SRR arrays and toroidal metamolecule by using double exposure e-beam lithography with precise alignment technique, and then their resonance behaviours are studied in optical region. We proposed a three-dimensional toroidal structure that supported toroidal resonance under normal incidence with large incident angle tolerance for more efficient electromagnetic energy harvesting. The electric as well as magnetic energy are effectively confined within the toroidal structure, these properties have promising applications in the field of plasmonics, such as integrated 3D plasmonic metamaterials, plasmonic biosensor and lasing spaser.

9163-23, Session 6

Where is next metamaterials moving forward? *(Invited Paper)*

Ai Qun Liu, Nanyang Technological Univ. (Singapore); Din Ping Tsai, National Taiwan Univ. (Taiwan); Nikolay I. Zheludev, Univ. of Southampton (United Kingdom)

Meta-fluidic-materials aim at manipulating light and metal-liquid flow in the microchannel, and exploiting their interaction to create highly versatile devices has received significant scientific interests in many areas. The novelties of the integrated meta-fluidic-material are two-fold. First, metal-fluids can be used to carry substances for analysis in highly sensitive optical micro-devices. Second, metal-fluids can also be exploited to control light, making them tunable, reconfigurable and adaptive. In this paper, the state-of-the-art of meta-fluidic-material research is reviewed with breakthrough innovations in optical and photonic devices, including the high potential applications of meta-fluidic-material in biophysical, biochemistry and biomedical studies.

Meta-fluidic-materials represent a new paradigm for designing light-manipulating devices, such as cloaks, transformation optics and field concentrators, through the engineering of electromagnetic space using materials with spatially variable parameters. We demonstrate that a laminar metal-liquid flow in microfluidic channel exhibits spatially variable dielectric properties that support novel wave-focusing and interference phenomena. This work provides new insight into the unique optical properties of meta-fluidic devices and their potential applications.

Meta-fluidic-material is not only to change the material properties through tuning or reconfiguring the unit element structure size or shapes, which is changed by the metal-liquid flow in the microchannel. It is significant breakthrough research for the meta-fluidic-material to demonstrate new materail with new physics phenomena that are never been observed before. In the paper, the different types of meta-fluidic-material will be presented with some future industry applications.

9163-25, Session 7

Mode control and loss compensation of propagating surface plasmons *(Invited Paper)*

Zhili Jia, Deng Pan, Hong Wei, Hongxing Xu, Institute of Physics (China)

Nanophotonic plasmon circuits may play important roles in next-generation information technology as semiconductor-based electronics is approaching the physical limit. The functions of such circuits rely on the rigorous control of plasmon propagation. One important aspect of such control is controlling the conversion of different plasmon modes for designed plasmon routing in complex nanophotonic networks. Here, we experimentally prove that the conversion of plasmon modes occurs widely in metallic nanowire waveguides, the basic components of plasmonic circuits, by introducing local structural symmetry breaking. In further simulations for the structure of a nanowire with a particle in its proximity, it is shown that the mode conversions originate from the redistribution of electric field in the wave front which is caused by the scattering of localized modes in the nanogap and on the nanoparticle. The different spin of incident photons can also control different plasmon modes in metal nanowires. This mode conversion and spin effect can be applied to flexibly control the plasmon propagation behavior in plasmonic nanowire networks.

9163-26, Session 7

Confined Tamm plasmons lasers *(Invited Paper)*

Joel Bellessa, Clementine Symonds, Guillaume L'Heureux, Univ. Claude Bernard Lyon 1 (France); Jean-Jacques Greffet, Jean-Paul Hugonin, Institut d'Optique Graduate School (France); Pascale Senellart, Aristide Lemaître, Lab. de Photonique et de Nanostructures (France)

Plasmonic Tamm states are interface modes formed at the boundary between a distributed Bragg mirror and a metallic layer. Their optical properties lie in between surface plasmons and microcavity photonic modes. In particular, the losses are reduced compared to a conventional plasmon. We will describe some features of semiconductor quantum wells coupled to extended Tamm modes, like strong coupling with the excitons and lasing. The main advantage of the Tamm modes lies in the easy confinement of the mode which can be obtained only by structuring the metallic part of the structure. The reduction of the mode volume leads to an efficient control of the spontaneous emission (increased beta factor), making Tamm confined structures well suited for single photon emitters and lasers. We demonstrate that confined Tamm plasmon modes can be advantageously exploited for the realization of new kind of metal/semiconductor lasers. Laser emission is studied for Tamm structures with various diameters of the metallic disks which provide the confinement. A reduction of the threshold with the size is observed. The competition between the acceleration of the spontaneous emission and the increase of the losses leads to an optimal size, which is in good agreement with calculations. Polarization effects in asymmetrical Tamm structures will also be discussed.

9163-27, Session 7

Surface Plasmon Mediated Inverse Polarization Transmission through Metallic Gratings in Deep Ultraviolet Band

Guoguo Kang, Chi Quan, Xiaodi Tan, Beijing Institute of Technology (China)

Inverse polarization transmission of light, with the TE transmittance ηTE largely exceeding the TM transmittance ηTM, through subwavelength metallic gratings at certain wavelength in deep ultraviolet band is theoretically investigated. By using the Fourier modal method and the planar waveguide theory, we show that the light transmission involves both the surface plasmon and the low-loss waveguide modes. Strong coupling of the incident wave to surface plasmon polariton results in the minimum in TM transmittance, whereas the coupling to the low-loss mode leads to the TE transmittance maximum. The established physical mechanism is sufficient to explain the inverse polarizing phenomenon observed in aluminum grating at the wavelength of 193nm, which may lead to important applications such as effective and compact polarizer used in DUV lithography.

9163-28, Session 7

Highly tunable ultra-narrow-resonances with optical nanoantenna phased arrays in the infrared

Shiqiang Li, Robert P. H. Chang, Northwestern Univ. (United States)

We report our recent development in pursuing high Purcell-Factor plasmonic resonances, with vertically aligned 2-D periodic nanorod arrays. Due to the freely tunable antenna resonances of the nanorod, through material properties (I.e. Plasma frequency and damping factor), the length of the nanorod, and the orthogonal polarization direction to the lattice surface, the 2-D vertically aligned nano-antenna array can have high-Q resonances tunable from near infrared to THz regime (Markel-Zou-Schatz resonance). The Q-factor in combination with the small mode volume gives a Purcell factor which could potentially be applied to various enhanced nonlinear photonics or optoelectronic devices. The 'hot spots' around the nanorods can be freely harvested as no index-matching is necessary. The resonances maintain its Q-factor with the change of refractive index, which is of great interest for molecular sensing. We also present a proof-of-concept realization of the proposed structure and it's optical measurement, which agree extremely well with theory and simulations. The demonstrated Q factor is above 400 and the field intensity enhancement is about four orders of magnitude.

9163-29, Session 7

Controlling the optics of sub-nanometer plasmonic cavities with graphene and other 2D atomic-sized layers

Christos Tserkezis, Centro de Fisica de Materiales (Spain); Jan Mertens, Daniel O. Sigle, Anna L. Eiden, Univ. of Cambridge (United Kingdom); Fumin Huang, Queen's Univ. Belfast (United Kingdom); Antonio Lombardo, Univ. of Cambridge (United Kingdom); Zhipei Sun, Aalto Univ. (Finland); Ravi S. Sundaram, Univ. of Cambridge (United Kingdom); Alan Colli, Nokia Research Ctr. UK (United Kingdom); Silvia Milana, Andrea C. Ferrari, Univ. of Cambridge (United Kingdom); Javier Aizpurua, Centro de Fisica de Materiales (Spain); Jeremy J. Baumberg, Univ. of Cambridge (United Kingdom)

Metallic nanoparticle dimers are particularly attractive plasmonic units, both from a theoretical and an experimental point of view. While recent advances in nanofabrication push rapidly towards minimising the interparticle distance, achieving sub-nanometer gaps, for which exciting quantum or nonlocal phenomena become relevant, is still challenging. An alternative, easier route is to consider a metallic nanoparticle placed on a metallic substrate, and study its interaction with its mirror image. Appropriate spacers between metallic interfaces prevent conductive contact. Here we propose the use of novel two-dimensional materials such as graphene as spacers. A single graphene monolayer acts as a very thin spacer (0.34 nm), while increasing the number of graphene layers leads to controllable, reproducible "quantised" sub-nanometer

gaps. By illuminating the system at large angles of incidence we show that an optical response similar to that of a metallic nanoparticle dimer is reproduced. For relatively thick spacers, a bonding dipole-like mode is excited in the near-infrared range of the spectrum, redshifting as the spacer thickness decreases. Reducing the thickness of the spacer to a single graphene monolayer leads to strong interaction that allows for the bonding quadrupole-like mode to distinctively appear in the scattering spectra. Finally, we show that additional control of the optical response of such dimers can be achieved by using different spacers, such as MoS2 or CdSe, and/or by generating flat facets at the contact of the nanoparticles with the substrate.

9163-30, Session 7

Helium-ion beam modification and tunable gap loading of plasmonic nanoantennas *(Invited Paper)*

Otto L. Muskens, Univ. of Southampton (United Kingdom)

Control over the resonances of plasmonic antennas is of considerable interest for their applications in nonlinear optics, sensing and spectroscopy. We show that helium-ion beam milling allows achieving extreme control over nanometer-sized gaps, including 30-nm deep gaps with widths below 5 nm, and vertically milled partial gaps [1]. The linear and nonlinear optical response of antennas with partially conducting bridges is investigated using single-particle spectroscopy, revealing that a bridge of nanometer height is sufficient to change the loading from capacitive to inductive type. Additionally, we demonstrate conductive antenna loading using transparent conductive oxides as active medium with unusual properties.

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9163-31, Session 8

Voltage-controlled strong coupling with metamaterial nanocavities: fundamentals and applications *(Invited Paper)*

Igal Brener, Alexander Benz, Sandia National Labs. (United States)

A single metamaterial resonator can act as very powerful "nanocavity" that allows for exquisite control over the magnitude and polarization of the optical fields near the resonator traces. We recently used these nanocavities to show strong coupling to optical excitations in semiconductors that can be designed and tailored through most of the infrared: i) intersubband transitions in quantum wells and ii) "epsilon near zero" (ENZ) modes. In both cases, these excitations can be influenced by the application of an electric field. This effect can be used for controlling the optical coupling and thus the overall spectral response of the metamaterial. I will present several examples of active, tunable metamaterials based on these effects.

9163-32, Session 8

Comparison of third-order nonlinear optical properties of colloidal gold nanoshells and nanorods

Marta Gordel, Wroclaw Univ. of Technology (Poland) and Ecole Normale Supérieure de Cachan (France); Joanna Olesiak-Banska, Radoslaw Kolkowski, Katarzyna Matczyszyn, Marek J. Samoc, Wroclaw Univ. of Technology (Poland); Malcolm Buckle, Ecole Normale Supérieure de Cachan (France)

We present a detailed comparison of the third-order nonlinear optical properties of colloidal gold nanoshells and gold nanorods in water suspensions, determined using the open- and closed-aperture Z-scan measurements performed with femtosecond laser pulses, in a broad range of wavelengths. The studies were carried out with attention being paid to having laser pulse energies well below the threshold of nanoparticle melting, so gold nanoshells and gold nanorods were stable during the laser irradiation [1]. The two-photon absorption coefficient (?2), the nonlinear refractive index (n2), the two-photon absorption cross-section (?2) and the saturation intensity for one-photon absorption (ISat) were evaluated in the 530-1200 nm wavelength range. [2]

For both gold nanorods and nanoshells the nonlinear absorption is dominated by absorption saturation, however, two-photon absorption is also clearly seen in some wavelength ranges. For the nanorods the longitudinal surface plasmon (l-SPR) range is dominated by saturated absorption while in the transverse surface plasmon resonance (t-SPR) range the two-photon absorption (2PA) properties dominate [2]. The gold nanoshells with the thinnest shell show two-photon absorption in the range between 530-600 nm, the estimated value of two-photon absorption cross-section ·2 is 5.12 ·1010 GM/cm2, longer wavelengths are dominated by absorption saturation We have found that the reciprocals of saturation intensities are the highest in the maximum of one-photon absorption (1PA) range for all studied nanoshells, however they decrease with the increase of a shell thickness.

The value of the merit factor ·2/M (two-photon absorption cross section scaled by the molecular weight) for gold nanorods (10nm x 35 nm) is equal to 7.5 (GM ·mol/g) at 530 nm [2], for the gold nanoshells it is markedly lower: 1.9 (GM ·mol/g) at 530 nm and 2.6 (GM ·mol/g) at 600 nm.

We have proved that gold nanorods are more efficient in absorbing light than gold nanoshells. Additional features such as: low cytotoxicity, facile immunetargeting, nonsusceptibility to photobleaching or denaturation makes them excellent probe for bioimaging.

References:

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9163-33, Session 8

Field enhanced plexitonic coupling between InAs quantum dot and silver film: highly sensitive plasmonic composite

Venus Dillu, Preeti Rani, Ravindra K. Sinha, Delhi Technological Univ. (India)

Plasmonics has become de facto dominating technology with important applications such as nano scale wave guidance, nano-circuitry, sensing, spectroscopy, imaging, lasing, solar cells etc. These applications in turn depend on the plasmon resonance that plays a key role in all the state-of-art devices. But as dimensions of the metallic nanostructures involved in the plasmonic devices decrease below 10 nm, the plasmon resonance becomes more sensitive to the quantum nature of the conduction electrons. These quantum-size effects arising due to nanoscale geometry or sub-nanometer gaps are difficult to explain using conventional plasmonics due to weak optical scattering and require exhaustive research.

In the present work, we study the field enhancement in plasmonic composite of indium arsenide (InAs) quantum dots (QD) of diameter d = 10 nm, arranged in hexagonal lattice on a silver film. The intensity is traced by scanning the absorption spectra for the system, resulting in highly sensitive composite. We found that the behaviour of the plasmonic composite changes by varying the thickness of metal film. It is observed that the sensitivity of the composite increases with decreasing the thickness of metallic film and the quantum-size effects dominate at sub-nanometer gap.

The interaction of quantum dot exciton with the plasmons of the silver metal causes transverse plexitonic coupling between the QD and silver, resulting in ultra high local field enhancement at the interface whereas the energy propagates longitudinally due to resonating quantum plasmonic tunnelling. The proposed system shows promising applications in lasing, sensing and spectroscopy.

9163-34, Session 8

Ultrafast silicon nanoplasmonic barristor

Shawn R. Greig, Abdulhakem Y. Elezzabi, Univ. of Alberta (Canada)

We present a detailed investigation of a silicon based CMOS compatible nanoplasmonic barrier transistor. A Si waveguide core is located between upper and lower Cu electrodes with a W grid buried in the Si core. The structure is excited with an 84 fs pulse centred around 1.55 µm, that becomes highly confined to a surface plasmon mode at the upper Cu-Si interface which decays away towards the W grid. Electrons are generated in the Si through two-photon absorption (TPA) of the nanoplasmonic field near the upper Cu electrode. Due to a high spatial gradient in the nanoplasmonic field the electrons experience unequal acceleration/deceleration from a ponderomotive potential, which allows them to achieve a distribution of energies as they approach the W grid. An effective energy barrier is created by applying a negative potential to the grid, thus controlling the number of electrons passing through it. Electrons that do pass through the grid reach the bottom Cu electrode where they are collected, creating a net current between the Cu electrodes. By varying the nanoplasmonic field and sweeping the grid voltage, the device exhibits a triode like behaviour. Increasing the nanoplasmonic field increases the number of TPA generated electrons and thus increases output current. Alternately, applying a more negative grid voltage creates a higher energy barrier which lowers the output current. The device is able to produce a pulsed output current of 11.7 mA/µm within 150 fs in a compact footprint.

9163-138, Session 8

Hybrid plasmonic platform for integrated nonlinear optical applications

Stefano Palomba, Fernando J. Diaz, The Univ. of Sydney (Australia); T. Hatakeyama, Junsuk Rho, Alessandro Salandrino, Kevin O'Brien, Univ. of California, Berkeley (United States); Xiang Zhang, Univ. of California, Berkeley (United States) and Lawrence Berkeley National Lab. (United States)

Fast transfer and processing of information are crucial to our modern society. They are mostly carried out by a combination of electronics, for processing the information and converting the outcome into light signals, and photonics, for transmitting those light signals over long distances via optical fibres. However, these traditional roles are not enough to fulfil the increasing demands for more and more information. Electronics equipment has become increasingly the bottleneck because of its bulkiness, its high power dissipation and consumption, its slow processing capabilities, and its vulnerability to electromagnetic interference. Being able to take over some tasks from electronics requires light to interact with itself, which does not happen at low light intensities. Two approaches have been explored to exploit substantial nonlinear phenomena: (i) transparent materials like glasses or semiconductors (photonics), which cannot compress light more than half a wavelength and thus require long propagation distances, leading to large linear dimensions; (ii) opaque, absorbing materials like metals (plasmonics), which can enormously compress light, giving rise to huge light intensities, so long propagation lengths are not required, leading to compact structures. However, the high losses tend to prevent this approach from reaching its full potential.

We present an alternative approach which combines the best characteristics of metals and dielectrics into a hybrid structure, which exhibits high light intensities, moderate losses and on-chip compatibility. The basic structure of every on-chip photonic device is a waveguide, which in this case is constituted by a nonlinear dielectric material (core), sandwiched between a metallic layer (plasmonic structure) and another dielectric material.

Such a hybrid plasmonic waveguide (HPWG) shows an increasing interpulse four-wave mixing (4wm) generation as a function of a decreasing in core thickness. Hybrid plasmonic architectures promise to be the keystone for future on-chip photonic signal processing and nonlinear optical devices.

9163-35, Session 9

Plasmon-exciton coupling between silver nanowire and two quantum dots *(Invited Paper)*

Qiang Li, Hong Wei, Hongxing Xu, Institute of Physics (China)

Controlling the interaction between single surface plasmons and individual quantum emitters is an outstanding problem in quantum science and engineering. Here we manage the coupling strength between a silver nanowire and individual quantum dots (QDs) by controlling the QD-nanowire separation distance. By using an atomic force microscope to manipulate a silver nanoparticle to create a nanogap between a silver nanowire and a Ag nanoparticle, the efficient coupling of the quantum dot in the nanogap with the silver nanowire is demonstrated by the enhanced emission intensity and the reduced fluorescence lifetime. We also experimentally realize resolving single plasmons generated by a pair of QDs on a silver nanowire. The separation between the two QDs is ranging from micrometers to 200 nm within the diffraction limit. The accurate position of each QD and the conversion efficiency of the exciton-plasmon coupling are obtained.

Nanoplasmonic devices are promising for next generation information and communication technologies because of their capability to confine light at subwavelength scale and transport signals with ultrahigh speeds. However, ohmic losses are inherent to all plasmonic devices so that further development of integrated plasmonics requires efficient in situ loss compensation of signals with a wavelength and polarization of choice. Here we show that CdSe nanobelt/Al_2O_3/Ag hybrid plasmonic waveguides allow for efficient broadband loss compensation of plasmonic signals of different polarizations at room temperature using an optical pump and probe technique.

9163-36, Session 9

Nanoplasmonic hydrogen sensing *(Invited Paper)*

Carl Wadell, Svetlana Syrenova, Christoph Langhammer, Chalmers Univ. of Technology (Sweden)

We will discuss how localized surface plasmon resonance (LSPR) based hydrogen sensing and spectroscopy has evolved. The field started with so-called direct hydrogen sensing schemes, which track the LSPR in palladium nanoparticles as hydrogen is absorbed. This concept was then followed by so-called indirect sensing techniques where inert plasmonic nanoantennas (e.g. Au or Ag) are used to probe the hydride formation process in adjacent nanoparticles. Using examples from our recent efforts, we will discuss how such plasmonic hydrogen sensors are of interest both from the point of reaching a fundamental understanding of hydrogen metal interactions at the nanoscale, and how they can be utilized as all optical gas sensors in a future hydrogen economy. Further developing the indirect sensing scheme, we will also illustrate how it becomes feasible to study hydrogen metal nanoparticle interactions at the individual particle level by designing appropriate nanoantenna arrangements. We will illustrate the strength of single particle studies compared to ensemble ones by highlighting the unique possibility to characterize the studied particle in detail by means of complementary techniques such as electron microscopy, and correlate the influence of particle size and shape on the metal hydrogen interaction at the nanoscale. This is important because such effects are hard to track in ensemble measurements as they are usually hidden due to size and shape distributions of the sample particles.

9163-37, Session 9

Observing charge transfer plasmons in nanocuboid dimers with large gaps

Ping Bai, A*STAR Institute of High Performance Computing (Singapore); Shu Fen Tan, National Univ. of Singapore (Singapore); Lin Wu, A*STAR Institute of High Performance Computing (Singapore); Michel Bosman, A*STAR Institute of Materials Research and Engineering (Singapore); Christian A. Nijhuis, National Univ. of Singapore (Singapore)

Charge transfer plasmon (CTP) is important in various applications including nano-electronics, chemical catalysis, nonlinear optics, and single molecule sensing. However, the CTP mode has only been predicted theoretically to occur through direct tunneling when the gap is reduced to ~ 0.4 nm, which is beyond the reach of current state-of-the-art fabrication technology. In order to experimentally observe the CTP in a relative larger gap between two metallic nanoparticles, we consider: 1) Using nanocuboids to increase the area of the cross-section. Larger cross-section can provide larger conductance if conductivity is the constant. 2) Choosing plasmonic metal with low work function such as Ag (4.26 eV) instead of Au (5.1 eV) for the nanocuboids to reduce the intrinsic tunneling barrier height. 3) Filling the gap with molecule insulators, such as self-assembled monolayers (SAM), instead of leaving it as vacuum. In this case, the tunneling barrier height depends on the alignment of the metal's Fermi level with the energy gap of the molecule insulators between the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO). Our simulations predict that the Au-vacuum-Au system requires a gap field on the order of 1010 V/m but the Ag-SAM-Ag system only requires a gap field on the order of 108 V/m to excite the CTP, which is within the reach of electron energy loss spectroscopy (EELS). We chemically synthesized the Ag nanocuboids, coated them with the SAM (e.g. 1,2-ethanedithiolates), assembled Ag-SAM-Ag dimers on a Si3N4 membrane, and finally excited and measured CTPs with EELS. We first time observed the CTP through the Ag-SAM-Ag dimers with a gap around 0.6nm and the Ag-SAM/SAM-Ag dimers with a gap around 1.2nm. This finding shows that the CTP could be excited in a large-gap dimer with longer molecules to perhaps 4-5nm and makes one more step for applying the CTP.

9163-38, Session 10

Simultaneous detection of nanoscale electric and magnetic fields *(Invited Paper)*

Laurens K. Kuipers, FOM Institute for Atomic and Molecular Physics (Netherlands)

Control of light at the nanoscale lies at the heart of the field of plasmonics. Crucial to the advances in the field is an improved understanding of the nanoscale behaviour of light, enabled by direct observations of the local electric fields near photonic nanostructures. The advent of metamaterials that interact with the magnetic component of light, has led to schemes to measure the nanoscale magnetic field. However, these metamaterials interact not only with the magnetic field, but also with the electric field of light. We show the simultaneous detection of both electric and magnetic fields with subwavelength resolution [1]. The simultaneous detection originates in the electro-magnetic response of our metallo-dielectric aperture probe of our near-field microscope [2,3]. By explaining our measurements through reciprocal considerations, we create a route towards designing probes sensitive to specific desired combinations of electric and magnetic field components.

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9163-39, Session 10

Imaging of rectified plasmonic fields on nanoantennas with single nanometer precision

Curtis J. Firby, Abdulhakem Y. Elezzabi, Univ. of Alberta (Canada)

Our experiments demonstrate high resolution direct imaging of plasmon localization with the use of a scanning tunneling microscope (STM). STMs have the ability to simultaneously record both the tunneling current and topography of a sample with sub-nanometer precision. The gap between the STM tip and a gold nanoplasmonic antenna's surface creates a nonlinear tunneling junction that can rectify plasmonic fields. Modulating an incident optical signal produces modulated evanescent fields that interact with the junction, creating an additional current component superimposed on top of the traditional tunneling signal. This signal was shown to be solely related to the field rectification in the junction. Thus, this component was isolated from the total tunneling current measured by the STM via lock-in detection, and was used to map out the plasmonic field intensity over the surface of the nanoantenna. Correlating the current signals with the topographical images of the excited plasmonic nanoantenna allowed us to map out the plasmonic field localization within nanoscale fissures between the grains of the gold surface with a remarkable resolution of 1nm, measured in comparison to the topographical features in which they reside. The resolution in these experiments was limited only by the device size, STM scan window, and scanning speed, so this technique can be applied to potentially create angstrom resolution images of plasmonic resonances on a variety of structures.

9163-40, Session 10

Laser-directed deposition of silver nanostructures

Anatoliy O. Pinchuk, Ke Jiang, Kathrin Spendier, Univ. of Colorado at Colorado Springs (United States)

We report here, a new method for the laser assisted deposition of silver nanoparticles on glass and plastic substrates that does not require any surface treatment or modification. Deposition of silver nanoparticles from an aqueous solution was observed under illumination of a substrate with a focused laser beam. The wavelength of the laser which drives the deposition is near the surface plasmon resonance (SPR) wavelength of the nanoparticles, highlighting the crucial role of an induced and SPR enhanced dipole moment in the nanoparticles. SPR enhancement of the induced dipole in the nanoparticles was confirmed through total internal reflection fluorescence microscopy and has not previously been reported. Longer wavelength lasers did not cause the deposition of these nanoparticles, which demonstrates the size dependence of their SPR wavelength and allows for the selective placement of different sized particles based on the deposition laser line selected. Complete surface coverage can occur in less than one minute and precise control of the deposition area is possible.

9163-41, Session 10

Plasmonic optoelectronics on Si *(Invited Paper)*

Pierre Berini, Anthony Olivieri, Univ. of Ottawa (Canada)

Metallic nano-gratings of rectangular cross-section operate as a coupling structure that couples broadside p-polarised incident light to surface plasmon polaritons (SPPs) propagating on an underlying thin metal film. When deposited on a Si substrate the structures become useful as infrared (1310, 1550 nm) intensity modulators or photodetectors, exploiting SPP-enhanced carrier refraction in Si, or SPP-enhanced internal photoemission, respectively. The electro-optical performance of such structures is assessed over a broad optical wavelength range as a function of geometrical parameters, including grating thickness, pitch, and duty cycle. Various materials are considered, including materials that are standard for CMOS electronics. Electrical bandwidths in the tens of GHz are predicted for modulators and detectors. Their area can be extremely small, but in practice is set to the area of a tightly focussed incident optical beam. The structures proposed are fabricated via metal evaporation and lift-off, with the nanogratings defined by electron beam patterning.

9163-42, Session 11

Plasmonic enhancement of charge carrier photogeneration in conjugated polymers *(Invited Paper)*

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We demonstrate a new concept for enhancing charge carrier photogeneration in conjugated polymers by resonant particle-plasmons. Charge carrier density is evaluated by probing photoinduced absorption and Infra-Red Active Vibrational Modes (IRAV) of the polymer. This concept may be used to enhance power conversion efficiency of organic photovoltaic cells.

9163-43, Session 11

3D-FEM analysis of SPP excitation through nanoholes in asymmetric metal-insulator-metal structure at tip of circular truncated conical fiber

Yasushi Oshikane, Osaka Univ. (Japan); Kensuke Murai, National Institute of Advanced Industrial Science and Technology (Japan); Motohiro Nakano, Osaka Univ. (Japan)

3D-electromagnetic (EM) analysis of surface plasmon polaritons (SPPs) excited by a single-mode (SM) propagation of visible lightwave in an optical fiber has been studied with a 3D-FEM package based on a finite element method. End of the fiber is formed to be a circular cone by wet etching process, and is FIBed to make a circular truncated conical shape with a flat circular surface a few micrometers in diameter. The flat end is covered with three layers of asymmetric metal-insulator-metal structure, thin metallic layer (M1), thick insulator layer (I), and thick metallic layer (M2), respectively. The outermost M2 layer has FIBed nanoholes to convert light waves at the extremity of the fiber into SPPs efficiently, and a bright tiny point light source will be generated on the surface of the M2 layer. In this study, the 3D-FEM models consists of both the MIM structure and the shrinking optical fiber tip coated with a metallic thin film has been designed and analyzed numerically. By applying perfect electric conductor and perfect magnetic conductor to planes containing the axis of rotation, the FEM model has a quarter of the circular truncated conical shape. The FEM analysis is formed in two steps. At the first step, a FEM mode analysis is performed to obtain a solution corresponding to the SM propagation in the fiber. The second level of action is the FEM analysis of EM field in the whole of model to find a stationary solution with the solution of mode analysis. Characteristic of wavelength-dependent excitation, propagation, and focusing of the SPPs will be presented with several experimental results of trial products of the fiber tip.

9163-44, Session 11

Surface plasmon decay in nanostructured systems *(Invited Paper)*

Prineha Narang, Ravishankar Sundararaman, Adam S. Jermyn, William A. Goddard III, Harry A. Atwater Jr., California Institute of Technology (United States)

Typical theoretical descriptions of the optical response of plasmonic systems have successfully used classical electromagnetic models to account for absorption, though quantum calculations have been applied to certain plasmonic phenomena such as coupling between nanoparticle dimers. Recently we analyzed the quantum decay of surface plasmon polaritons[1] and found that the prompt distribution of generated carriers is extremely sensitive to the energy band structure of the plasmonic material. In this context we present theory and calculations that elucidate the decay dynamics of plasmons to excited hot carriers in nanostructured plasmonic systems, based on the quantization of plasmon fields in conjunction with detailed electronic structure. We have developed a general theoretical and computational framework using a multi-scale model that combines long-range electromagentic solvers for the plasmons with density functional theory in a maximally-localized Wannier basis for the electrons. With a diagrammatic approach to processes involving plasmons, electrons and phonons built upon this model, we present realistic fi rst principles calculations for nanostructured plasmonic systems.

9163-45, Session 11

Tunable plasmons in atomically thin gold nanodisks

Alejandro Manjavacas, Rice Univ. (United States); Francisco Javier García de Abajo, ICFO - Institut de Ciències Fotòniques (Spain)

The ability to modulate light at high speeds is of paramount importance for telecommunications, information processing, and medical imaging technologies. This has stimulated intense efforts to master optoelectronic switching at visible and near-infrared (vis-NIR) frequencies, although coping with current computer speeds in integrated architectures still remains a major challenge. As a partial success, midinfrared light modulation has been recently achieved through gating patterned graphene [1].

Here [2] we show that atomically thin noble metal nanoislands can extend optical modulation to the vis-NIR spectral range. We find plasmons in thin metal nanodisks to produce similar absorption cross-sections as spherical particles of the same diameter. Using realistic levels of electrical doping, plasmons are shifted by about half their width, thus leading to a factor-of-two change in light absorption. These results are supported by a microscopic quantum-mechanical calculations based on the random-phase approximation (RPA), which we compare with classical simulations obtained solving Maxwell's equations using tabulated dielectric functions. Both approaches result in an excellent agreement for nanodisks with diameters above 13 nm, although quantum confinement and nonlocal effects play an important role for smaller sizes.

We analyze, as well, the optical response of periodic structures created from these thin nanostructures, for which we predict absorbances of

25% for metal layer filling fractions of 40%. These results hold great potential for the development of electrical vis-NIR light modulation in nanoscale devices.

[1] J. Chen et al., Nature (2012), Z. Fei, et al., Nature (2012).

[2] A. Manjavacas and F.J Garcia de Abajo, submitted (2014).

9163-46, Session 11

Optical nanogap matrices for plasmonic enhancement applications

Stephen J. Bauman, Desalegn T. Debu, Avery M. Hill, Eric Novak, Univ. of Arkansas (United States); Douglas Natelson, Rice Univ. (United States); Joseph B. Herzog, Univ. of Arkansas (United States)

Plasmonics, a field studying the interaction between light and charges on metal surfaces, continues to grow as an interdisciplinary field spanning physics, engineering, and nanoscience research with applications that include enhance photovoltaic cells, plasmonically enhanced spectroscopy, and other optoelectronic devices. Plasmons have been shown to enhance or otherwise manipulate the electromagnetic field of light waves incident on a metal surface. Nanoscale structures and features have proven critical in controlling the plasmons for specific applications. The use of a nanoscale region or gap between other larger nanoscale structures allows for focusing of light at the nanoscale, leading to significant increases in the local electric field magnitude and optical gain in the gap. This optical enhancement is inversely proportional to the gap size, therefore it is of interest to fabricating gaps smaller than the typical electron beam lithography fabrication procedures. Thus, we make use of a previously developed self-aligned technique that can produce nanogaps with widths that can be controlled to be only a few nanometers wide (<5 nm). This work further develops the self-aligned technique by working towards making plasmonic nanostructures with nanoscale gaps in two dimensions. This technique enables the fabrication of a large-area matrix of such structures which will expand the current limits of plasmonic nanogap fabrication capability and prove useful for enhanced photovoltaics. Furthermore, this unique nanofabrication technique could also allow for other structures that could prove beneficial in various nanoscience studies and applications, in addition to the study of the physics of plasmons and nano-optical behavior.

9163-47, Session 11

Plasmon-enhanced photothermal response in heterogeneous metallic trimers

Seyfollah Toroghi, Pieter G. Kik, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

The ability of metallic nanoparticles to generate heat under optical illumination is of significant interest due the strong, rapid, and fast thermal response that can be achieved. This enables thermally assisted applications including photothermal and optoacoustic imaging and thermal nonlinear switching. For isolated metal nanospheres, the temperature change that can be induced by short pulsed illumination at a fixed fluence is known to become size independent in the quasi-electrostatic limit. Here, we demonstrate that the achievable temperature change can be increased by orders of magnitude by engineering the local environment of the particle. In particular, we investigate the optical and thermal response of a gold nanoparticle placed between two larger silver nanoparticles. Through numerical simulations we predict a temperature change of 100 K in a Ag-Au-Ag nanoparticle trimer consisting of two 80 nm diameter silver nanoparticles and a 10 nm diameter central gold nanoparticle in water shortly after a 20 nJ/mm2 pulse at 530 nm, compared to only 0.65 K for the isolated gold nanoparticle. It is shown through analytical calculations that this effect can be understood in terms of the hybridization of the silver dimer plasmon resonance and the gold nanoparticle resonance. The spherical shape of the elements of the trimer is expected to withstand relatively high temperatures without significant structural degradation. Notably the predicted effects can be achieved using experimentally accessible particle sizes, and occur largely outside the range of quantum plasmonics and nonlocal effects. The proposed trimer appears amenable to large-scale fabrication through chemical synthesis.

9163-48, Session 12

Nanomechanical transduction in plasmonic systems *(Invited Paper)*

Ewold Verhagen, FOM Institute for Atomic and Molecular Physics (Netherlands)

I will present our experiments on the aforementioned systems that integrate Si3N4 nanomechanical oscillators with plasmonic resonances in nanoslits as well as single antennas. We investigate both sensitive nanomechanical transduction as well as pronounced optical forces. We demonstrate parralel readout of many plasmonic optomechanical systems, facilitated by their efficient free-space coupling and nanoscale footprint. Finally, we study optical interactions in hybrid plasmonic-dielectric systems, consisting of nanoantennas evanescently coupled to whispering gallery mode cavities. Scattering experiments reveal how the nanoantenna polarizability is affected in proximity to the microcavity. Simultaneously, the antenna-cavity coupling causes the cavity mode spectrum to be strongly altered by the presence of the nanoantennas. Interestingly, both antenna-induced blue and red shofts are observed, as well as both decreased and increased cavity quality factors, depending on the nanoantenna properties. By placing the nanoantennas on nanomechanical oscillators, we aim to directly observe nanophotonic forces and realize a new class of nanomechanical transducers and actuators.

9163-49, Session 12

Nano-scale patterns of molybdenum on glass substrate for use in super-resolution imaging with metamaterials

Han Li, Andrew M. Sarangan, Partha P. Banerjee, Univ. of Dayton (United States)

Photolithography is widely used to transfer a geometric pattern from a mask to a photoresist film, but the minimum feature sizes are limited by diffraction through the mask. Focused ion beam (FIB) and electron beam lithography (EBL) can be used when higher resolution is desired, but the write times are long and costly. Here, deep ultraviolet (DUV) interference lithography, which is a maskless technique is used as an alternative to produce high resolution patterns with linewidths as small as 100nm. Since metamaterials may have the property to overcome Abbe's diffraction-limit for super-resolving and imaging sub-wavelength objects, there is a need for fabricating objects with sub-wavelength feature sizes to characterize the performance of these metamaterials. The DUV interference lithography and reactive ion etching process can be used to fabricate the sub-wavelength patterns on metal. In this talk, we present our results of fabrication and characterization of sub-wavelength objects for visible wavelengths using molybdenum (Mo) of typical thickness 50 nm initially sputtered on a glass substrate. A DUV source at 266 nm is used. An anti-reflection layer followed by a high resolution negative tone photoresist is coated on the top of Mo film. The cross-linked photoresist created after the development and bake processes is used as a mask for etching. Fabrication of the sub-wavelength object is completed by reactive ion etching in a fluorinated plasma. Finally the quality of the sub-wavelength object is characterized using TE and TM polarized illumination.

9163-50, Session 12

Dirac-like surface plasmons in metallic honeycomb lattices with directional edge states *(Invited Paper)*

Siying Peng, Sondra L. Hellstrom, Harry A. Atwater Jr., California Institute of Technology (United States)

We have observed Dirac-like band structures of surface plasmons in metallic honeycomb lattices, similar to electronic band structures of graphene [1, 2]. Full wave simulations (FDTD) on an infinite honeycomb lattice of silver nano-pillars revealed hybridization of localized plasmonic modes between two neighboring pillars and the consequent formation of bonding and anti-bonding modes that are energetically degenerate at Dirac points with a relative phase of Pi. This phase difference is a manifestation of the Berry phase similar to that in graphene. We broke the inversion symmetry of the infinite honeycomb lattice by shifting the relative position of the two triangular sub-lattices. This inversion symmetry-breaking perturbation opened a band gap at the Dirac point. Simulations on finite ribbon of the perturbed lattice showed two edge states within the gap with opposite propagation directions.

We fabricated the silver nano-pillars honeycomb lattice structure on silicon nitride membranes with e-beam lithography and a lift-off process. The band structures are experimentally characterized via cathodoluminescent spectroscopy. In the CL measurement, electron beams are incident on the sample to excite the plasmonic modes. The scattered light due to the decay of the surface plasmon excitations is collected by a parabolic mirror and mapped to the momentum space, yielding a direct construction of the band structures in the Brillouin zone. Our results provide a new way to control propagation direction of surface plasmon edge states without backscattering by selective excitation.

1. “Dirac-like Plasmons in Honeycomb Lattices of Metallic Nanoparticles”, G. Weick, C. Woollacott, W. L. Barnes, O. Hess and E. Mariano, PRL, 2013

2. “Dirac Spectra and Edge States in Honeycomb Plasmonic Lattices”, D. Han, Y. Lai, J. Zi, Z. Zhang and C. T. Chan, PRL, 2009

9163-51, Session 12

Theory of the resonance shift of plasmonic nanoresonators for dielectric sensing *(Invited Paper)*

Weihua Zhang, Nanjing Univ. (China)

Plasmonic nanoresonators which exhibit resonance shifts upon the change of their local environment promise all the properties and capabilities required for the next generation ultrasensitive biochemical nanosensors. [1] To date, a large number of plasmonic nanosensors have been demonstrated with various designs and materials. However, the reported sensitivities have large variations without showing any general rules.

In this work, we therefore study the spectral sensitivity of plasmonic nanoresonators using an analytical method. We first derive the analytical expressions for the resonance frequency shifts of a dispersive plasmonic nanoresonator upon the adsorption of nanoparticles, covering by a thin layer of molecules, and changes of the bulk refractive index of the surrounding liquid using the perturbation theory.[2] We emphasize the role of material dispersion, one of the fundamental differences between plasmonic nanoresonators and nondispersive dielectric microresonators. Furthermore, we discuss the relation of resonance shifts to the local electric field enhancement and Q-factor. Our results show that the resonance shifts are only related to the geometry-induced electric field enhancement, and independent with the Q-factor. Finally, statistic analysis is performed to determine the limit of detection of the system in experiments.

This work establish a comprehensive theory for dispersive plasmonic nanoresonator sensor, and provides practical guidelines for designing plasmonic sensing, as well as active plasmonic devices.

[1] W. Zhang, L. Huang, C. Santschi, and O. J. F. Martin, Nano Lett. 10, 1006 (2010)

[2] W. Zhang, O. J. F. Martin, “Universal law for nanoparticle induced resonance frequency shift of subwavelength plasmonic nanocavities in the context of optical trapping” (in preparation)

9163-52, Session 12

Plasmonic nanostructuring through direct laser interference patterning

Yuanhai Lin, Tianrui Zhai, Xinping Zhang, Beijing Univ. of Technology (China)

Direct writing of plasmonic nanostructures is demonstrated by nanoscale-tensile-stress-induced patterning through interference crosslinking in a polymer film and by single-pulse interference ablation of a continuous gold film. Through direct exposing to the interference pattern between UV laser beams at 325nm, the polymer molecules get cross-linked, resulting in the reduction in both the thickness and the refractive index of the polymer film. This process has been used to fabricate polymeric nanostructures. However, nanoscale-tensile-stress was produced during the interference crosslinking process. Thus, the continuous gold film evaporated on the top of the polymer film was stretched into gold nanolines, which are actually the transfer of the polymeric pattern. Consequently, one-dimensional plasmonic nanolines or two-dimensional nanodots with strong plasmonic response were achieved.

Furthermore, gold nanostructures can be directly written into gold films by interference ablation using a single UV laser pulse, which operates at 355nm with a duration time of about 5 ns. The continuous gold film, which was evaporated onto an ITO-coated silica substrate with a thickness of about 18 nm, can be directly removed within the bright interference fringes with high laser intensity. The remaining gold within the dark interference fringes forms the plasmonic photonic nanostructures with the period tuned from 350 to 1000 nm. Due to the high thermal conductivity of the gold, strong heat transfer dominates the process of interference ablation for the fabrication of the ultimate metallic photonic structures. The experimental results enable better understanding of the thermal processes that are possibly involved in laser ablation, which is important for controlling and optimizing the spatial resolution of the directly written plasmonic photonic crystal devices.

9163-53, Session 13

Plasmonic enhancement of optical absorption, electroluminescence, florescence, and Raman scattering by metal nanoparticles: limits and comparison *(Invited Paper)*

Greg Sun, Univ. of Massachusetts Boston (United States)

Nanometer-scale metallic structures have been extensively studied as a way to dramatically modify optical properties of various optically active objects of similar dimensions such as atoms, molecules, or quantum dots that are placed in close proximity of these metallic structures. We present an analytical model that elucidates and establishes the enhancement limits of various optical processes including optical emission, absorption, photoluminescence (PL) and Raman scattering by single, as well as coupled metal nanoparticles. This model is capable of explaining the origin for the much greater Raman enhancement that has been observed in experiments while that for the seemingly similar PL process is far more modest.

9163-54, Session 13

Effect of nanoscale surface roughness on surface-tuned nanoparticle plasmon resonances *(Invited Paper)*

Chatdanai Lumdee, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Binfeng Yun, Southeast Univ. (China); Pieter G. Kik, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Plasmon resonant metal nanoparticles on substrates have been considered for use in several nanophotonic applications due to the combination of large field enhancement factors, broadband frequency control, ease of fabrication, and structural robustness that they provide. Despite the existence of a large body of work on the dependence of the nanoparticle plasmon resonance on composition and particle-substrate separation, little is known about the role of substrate roughness in these systems. This is in fact an important aspect, since particle-substrate gap sizes for which large resonance shifts are observed are of the same order of typical surface roughness of deposited films. In the present study, scattering spectra of 80 nm diameter gold nanoparticles on a gold film were acquired using dark-field single-particle spectroscopy. The measured data show a mean average resonance wavelength of 745 nm and a particle-to-particle spectral variation of 14 nm (one sigma). The measured results are compared with calculated scattering spectra of gold nanoparticles on corrugated gold substrates with a surface morphology based on measured atomic force microscopy data. By combining a statistical analysis of the measured surface features with electromagnetic simulations of likely local particle environments, it is demonstrated that the experimentally observed spectral variations can be explained by taking into account the film surface roughness. This study demonstrates that nanoscale surface roughness can become an important source of spectral variation for substrate tuned resonances that use small gap sizes. The implications of our findings on the design of reliable plasmonic biochemical sensing substrates will be discussed.

9163-55, Session 14

Eigenvector expansion of discrete-dipole approximation: application to the simulation of optical extinction and electron energy-loss spectroscopies of coupled metallic nanoparticles

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In this work, we are interested in the simulation of extinction and electron energy loss (EEL) spectra of isolated and coupled metallic particles. To achieve this, we have developed an efficient procedure based on the discrete-dipole approximation (DDA). Instead of directly solving the full system of dipoles, we calculate the eigenvalues and the associated eigenvectors of a geometric matrix describing each particle. These eigenvectors are then used as a truncatable basis in which an expansion of the DDA-quantities is made. By choosing carefully the eigenvectors, it is possible to truncate the basis to few terms compared to the complete set containing thousands of vectors. The response of the whole system is then obtained by adding interaction terms which account for multiple scattering between the particles. The advantage of this method is that it reduces significantly the size of the system of equations to be solved (and then the computational effort) when one considers multiparticle systems. Substrate effects can also be taken into account thanks to the dipole image method. Translated in the eigenvector expansion (EVE) formalism, these effects appears as interaction (i.e. multiple scattering) between the particles and their image. The proposed EVE procedure has been used to calculate EEL and extinction spectra of isolated and coupled metallic nanoparticles of various shapes and the results have been confronted to full DDA calculations to validate the approach.

9163-56, Session 14

Enhanced up-conversion in nanocrystals coupled to silver nanowires

Aneta Prymaczek, Kamil Ciszak, Institute of Physics, Nicolaus Copernicus University (Poland); Marcin Nyk, Wroclaw Univ. of Technology (Poland); Dawid Piatkowski, Sebastian Mackowski, Nicolaus Copernicus Univ. (Poland)

The up-conversion phenomenon is a sequential absorption of two or more IR photons and it leads to light emission at shorter wavelengths than the excitation wavelength. Typical ions used for up-converting are Er3+ and Tm3+, co-doped with Yb3+, as they exhibit the highest up-conversion efficiency, which is particularly important for anti-Stokes bioimaging. Recently, plasmon excitations have been applied for increasing the efficiency of up-conversion processes in nanocrystals doped with rare earth ions. In principle, under appropriately optimized physical conditions such as spectral matching and optimal distance, plasmon oscillations can lead to both enhanced absorption and emission rates of rare earth ions.

In this work we distinguished experimentally different processes that contribute the overall plasmon enhancement up-conversion. We studied hybrid nanostructures composed of NaYF4:Er3+/Yb3+ nanocrystals coupled to silver nanowires. Plasmon-enhanced absorption is demonstrated using linearly polarized laser light. Confocal anti-Stokes fluorescence microscopy images show very intense emission from nanocrystals coupled to nanowires oriented parallel to the polarization vector of incident light. This indicates that the nanowires efficiently collect IR radiation and transfer the excitation energy to nanocrystals leading to enhanced absorption. At the same time Fluorescence Lifetime Imaging Microscopy yields shortened fluorescence lifetimes of nanocrystals coupled to silver nanowires and illustrates plasmon enhanced emission rates due to the Purcell effect. Finally, by applying Back Focal Plane Microscopy, we proved that the fluorescence energy additionally excites propagating surface plasmon polaritons in the nanowires which distribute and reemit fluorescence as leakage radiation, contributing to the overall up-conversion enhancement. Overall, our observations demonstrate the complex interplay of energy transfer and dissipation in this plasmon-enhanced up-converting hybrid nanostructure.

9163-57, Session 14

Superradiance effect in multiple plasmonic resonators

Zongfu Yu, Univ. of Wisconsin-Madison (United States)

We developed a classical optics description of the superradiance for N resonators based on a multi-resonator multi-channel temporal coupled mode theory. Using the theory, we showed subtle absorption effects that are absent in the emission process, such as superradiance-induced transparency where the absorption is suppressed by up to N^2 times. To validate theoretical predications, we implemented the analogy of superradiance using graphene ribbons, optical resonators that offer deep subwavelength sizes as well as easy control of near-field interaction.

9163-58, Session 14

Generation and characterization of plasmonic nanostructures in glass surfaces by means of excimer and solid state laser irradiation

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Ihlemann, Laser-Lab. Göttingen e.V. (Germany); Thomas Rainer, boraident GmbH (Germany)

The localized formation of very small metal particles enables the generation of nanostructured materials, which are of interest for manifold applications as surface plasmon devices. This study investigates the space-selective precipitation of Ag and Ag/Au nanoparticles and the creation of appropriate arrays thereof in surface regions of dielectric matrices like glasses by means of ultraviolet laser irradiation (193 and 405 nm) below the ablation threshold. The Ag and Au ions were introduced into the soda-lime silicate glass using melting and ion exchange processes. After laser processing, the experimentally recorded spectra of optical spectroscopy demonstrated that the reduction of metal ions is caused by defect generation, for example the generation of electron hole centres, or by redox reactions with polyvalent ions. Finally, the agglomeration of neutral metal atoms and the growth of nanoscaled structures occur due to heating of the specimens as direct result of laser irradiation or by subsequent thermal treatments. The interesting surface plasmon resonances were registered in UV/Vis range as a function of sizes and origin of nanoparticles and of specific arrays like line or grating configurations. The simulation of absorption spectra by means of Mie theory and additional experiments of small angle X-ray scattering (SAXS) allowed to identify the resulting surface plasmon resonance in correlation with nanoscaled configurations of metal structures in the dielectric matrix.

9163-59, Session 14

Quantum nonlocal effects in individual and interacting graphene nanoribbons

Iván Silveiro, Juan Manuel Plaza Ortega, Francisco Javier García de Abajo, ICFO - Institut de Ciències Fotòniques (Spain)

We show that highly doped graphene ribbons can support surface plasmons at near-infrared frequencies when their width W is in the nanometer range. We rely on a quantum-mechanical approach to the optical response [1] that allows us to go beyond a classical local description in order to account for nonlocal and quantum finite-size effects. The latter are important for widths below W~10 nm, as revealed by comparison with classical theory [2]. The scaling law wp~(EF/W)^0.5 of the plasmon frequency wp with the Fermi energy EF and the ribbon width W is approximately maintained down to small sizes, despite some discrepancies originating in nonlocality. Specifically, the orientation of the edges relative to the graphene atomic lattice plays a crucial role, with zigzag edges contributing to damp the plasmons at energies above the Fermi level, due to the participation of electronic edge states. In contrast, armchair ribbons can support well defined plasmons at energies above EF. We also investigate the interaction between ribbons in close proximity. Strong hybridization between plasmons in periodic arrays is observed at small separations below a few nanometers. A substantial dependence on edge orientation and relative atomic alignment is observed. At larger separations, the dipolar interaction between ribbons becomes dominant. Analytical expressions are formulated that agree well with numerical results in the small and large separation limits. Besides the fundamental interest of this study, our work supports the use of narrow ribbons to achieve electro-optical modulation in the near infrared.

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9163-60, Session 14

Large chemically synthesized silver crystals for low-loss and active plasmonics

Chun-Yuan Wang, Hung-Ying Chen, Yu-Jung Lu, Shangjr Gwo, National Tsing Hua Univ. (Taiwan); Liuyang Sun, Xiaoqin Li, The Univ. of Texas at Austin (United States)

Surface plasmon polaritons (SPPs) supported on the noble-metal surfaces possess larger wavevectors than that of light at the same frequency from complete visible to the infrared range. Therefore, noble-metal nanostructures can function as near-field transducers in order to compress light below the diffraction limit and to realize novel applications such as plasmonic nanoantennas, nanolasers, and nanocircuits. However, the real-world applications of SPPs are very sensitive to plasmonic losses, which include (i) ohmic losses, (ii) in-plane scattering (e.g., grain boundaries), and (iii) far-field radiative scattering. Recently, several groups have demonstrated that ultrasmooth1 and single-crystalline2-5 noble-metal films1,2,4,5 and nanocrystals3 have lower plasmonic losses than those of polycrystalline films. For example, we had demonstrated low-threshold and diffraction-unlimited plasmonic nanolaser based on the epitaxial silver film4. Here, we report on novel chemical synthesis and plasmonic applications of macroscopic-sized, single-crystalline silver plates. In combination with the focused ion beam milling technique, we demonstrate that high-quality plasmonic nanocavities, nanocircuits, and nanoantennas could be fabricated on these plates. Furthermore, we have incorporated III-nitride semiconductor nanostructures as local coherent SPP sources (spasers) into these plasmonic structures for the possible realization of active integrated plasmonic systems.

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9163-82, Session PWed

Enhanced transient absorption of organic dyes induced by surface plasmons of silver nanoparticles

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Ability to control shape and size of silver nanoparticles enables us to produce nanoparticles with various useful optical properties, but for their application it is important to get high concentrations of nanoparticles. In this paper, we used reduced silver nitrate salt for forming of Ag clusters and chose hydrogen peroxide to control nanoparticles size. In this synthesis method we prepared high concentration (50 mM) nanoparticles.

After the characterization of the structure of silver nanoparticles using Transmission electron microscopy (TEM) and UV-VIS spectroscopy we observed that in our experimental samples nanoparticles formed on average of 50nm, 80 nm and 100 nm diameter and triangular shape, whose size was dependent from the hydrogen peroxide concentration. This result is also confirmed by high-intensity visible extinction band in the optical absorption spectra at 500-800 nm depending of NPs size resulting from localized surface plasmon resonance typical to silver nanoparticles. From these high concentration nanoparticles using spin coating method high densities of NPs in thin films can be obtained. In this work we presented how to get high concentration silver nanoparticles for application in organic solar cells.

9163-85, Session PWed

High sensitivity refractive index sensing in gold nanoslit arrays

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Extraordinary optical transmission (EOT) spectra of nano-aperture array are widely investigated since it was demonstrated by Ebbesen in 1998. The resonances of surface plasmons and cavity mode in some periodic nanostructures, such as nanohole and nanoslit, cause EOT in certain wavelengths. Since the resonant wavelength is changed under different surface conditions, the metallic nanostructures are expected to be good sensing elements. We investigate experimentally and theoretically the sensing performance of gold nanoslit array. Three-dimensional FDTD simulations are performed to analyze their transmission spectra and steady-state field intensity distributions. The nanoslit array pattern are defined by electron beam lithography, and transferred to gold film by ion milling process. We fabricated and measured several gold nanoslit arrays with varied period and width. The sensing performance of the gold nanoslit arrays are characterized via extinction spectra in various refractive index fluid environments. Geometrical investigation results of gold nanoslit arrays show that sensitivity approaches saturation as width of nanoslit is smaller than 70nm and is almost linearly proportional to the array period when nanoslit width is fixed. The highest sensitivity of the gold nanoslit arrays is 726nm/RIU, and the nanoslit arrays are demonstrated to be a superior choice of biosensor.

9163-86, Session PWed

Mode parity-controlled Fano and Lorentz resonances in plasmonic nanorods

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We present the experimental observation of spectral lines of distinctly different shapes in the optical extinction cross-section of metallic nanorod antennas. Surface plasmon resonances of odd mode parity display Fano interference in the scattering cross-section resulting in asymmetric spectral lines. Contrarily, modes with even parity appear as symmetric Lorentzian lines. Finite element simulations are used to verify the experimental results. The emergence of either constructive or destructive mode interference is explained with a semi-analytical 1D line current model. This simple model directly explains the mode-parity dependence of the Fano-like interference. Plasmonic nanorods are widely used as half-wave optical dipole antennas. Our findings offer a perspective and theoretical framework for operating these antennas at higher order modes.

9163-88, Session PWed

Plasmon coupling in upright magnetic SRR metamolecules

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In the past few years, a number of interesting designs have been proposed to generate artificial magnetism at optical frequencies using plasmonic metamaterials [1,2], but owing to the planar configurations of typically fabricated metamolecules that make up the metamaterials, the response to the incident magnetic field is very weak. To date a large majority of the manipulations on the plasmonic metamaterials are based on pure electric effects where only the electric component of the incident wave plays an active role. Still the quest to explore the interaction of metamaterials with the other half of the electromagnetics by expanding into the realm of magnetism that has been rarely ventured into is very much alive. One enabling element for this investigation is the fabrication of three-dimensional (3D) split ring resonators (SRRs) which behave as magnetic metamolecules sensitive to both the incident electric and magnetic fields upon excitation. However, the principle question on how the incident electric and magnetic fields interact with the plasmon hybridization of such 3D metamolecules still remains open. In this work, we study the magnetic plasmon response for isolated planar and 3D SRRs. And then we conduct experimental and numerical to investigate the coupling effect between incident fields and 3D SRR dimers by using oblique incidence which is able to vary the effective incident electric (magnetic) field that interacts with the metamolecules while maintaining the magnetic (electric) field unchanged for analyzing and tailoring the plasmon excitation at each plasmonic response. This work offers an important pathway to the realization of active manipulation of plasmon properties of metamaterials via magnetic coupling at optical frequencies.

9163-89, Session PWed

Optimizing the quantum dot-plasmon interaction in a nano gap waveguide

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Spontaneous emission (SE) of a Quantum emitter depends mainly on the transmission strength between the upper and lower energy levels as well as the Local Density of States (LDOS)[1]. When a QD is placed near a plasmon waveguide, LDOS of the QD is increased due to addition of the non-radiative decay and a plasmonic decay channel to free space emission[2-4]. The slow velocity and dramatic concentration of the electric field of the plasmon can capture majority of the SE into guided plasmon mode ( ).

This paper focused on studying the effect of waveguide height on the efficiency of coupling QD decay into plasmon mode using a numerical model based on finite elemental method (FEM). Symmetric and asymmetric gap waveguides were considered in this paper. Both waveguides are single mode and the QD is modeled as a dipole emitter. 2D simulation models are done to find normalized and 3D models are used to find probability of SE decaying into plasmon mode ( ) including all three decay channels. We show that changing gap height can increase QD-plasmon coupling, by up to a factor of 5 and an optimally placed QD can increase the QD-plasmon coupling up to a factor of 8. To make the paper more realistic we briefly studied the effect of sharpness of the waveguide edge on SE into guided plasmon mode. Preliminary GPW fabrication and testing are underway. Authors expect to compare the theoretical results with experimental outcomes in the future.

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9163-90, Session PWed

Transient plasmon-like modes in multi-level quantum emitter systems

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We model a nanoparticle of organic dye molecules as an ensemble of multi-level quantum systems in order to determine the conditions necessary to yield temporal optical field enhancement for different probe energies. By utilizing a time-dependent density-matrix approach and by examination of the role played by both radiative and non-radiative decay processes between energy levels, we explore how optical pump and probe fields may be used to control the permittivity of the nanoparticle as a function of time. When an appropriate value of the permittivity occurs, a plasmon-like mode will be produced. In this work, we investigate systems in which these plasmon-like modes can be generated at probe energies detuned from the atomic transitions and sustained for timescales dependent on the lifetime of a meta-stable level in our system. Our results suggest that these plasmon-like modes may generate temporal optical field enhancement and that such nanostructures open a new realm in nanophotonics in which transient behaviour can lead to phenomena that cannot be attained in the steady-state regime.

9163-91, Session PWed

Tailoring plasmonic field within two-color laser using metallic nanostructure for the generation of high harmonics

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We have theoretically investigated high-harmonic generation (HHG) and extreme-ultraviolet (XUV) radiation via nanoplasmonic field enhancement in a two-color laser field. We have proposed and optimized an asymmetric metallic nanostructure based on the finite element method (FEM). This asymmetric nanostructure could effectively enhance the incidence with two different wavelengths simultaneously. In order to tailor the plasmonic near-field, the asymmetric factor is introduced for this nanostructure in our work, which would affect its enhancement ability for the different incident wavelength. The electromagnetic properties of this asymmetric nanostructure are fully analyzed and discussed in temporal domain and spatial domain. Comparing with the case of the one-color field, this asymmetric nanostructure enables a broader bandwidth and smoother harmonic spectra under the condition of the two-color incidence field, which benefits the generation of broadband-isolated attosecond pulses. The theoretical simulations of the generated harmonic in enhanced laser fields via nanoplasmonic resonance are performed by the numerical solutions of the time-dependent Schrodinger equation. We have adopted the single active electron approximation and a softcore potential was employed in order to computer the high-harmonic spectra. By varying the parameter of the asymmetric nanostructure, and changing the relative phase of the two-color laser field, the influence to the temporal and spatial characteristics of the generated attosecond pulses are studied and analyzed. We also demonstrated that the isolated attosecond pulses were attained in the two-color enhanced field via the asymmetric nanostructure, while the attosecond pulse train appeared in the case of the one-color field. This work would have potential application in the time-resolved studies with high resolution.

9163-92, Session PWed

Optical spectra of noble metal nanoparticles supported on zeolites

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The synthesis and study of nanoparticles embedded in mesoporous materials is an important topic in nanoscience and nanotechnology. Metal nanoparticles dispersed over supports have found use as heterogeneous catalysts in many industries including fine chemistry, energy-related applications and environmental remediation. There is profound technological interest in zeolite based catalysts due mainly to its morphological properties that yield very high surface to bulk ratios. Zeolites are crystalline aluminosilicate materials comprised of a series of strictly uniform channels and cavities of nanosized dimensions repeating along the tri-directional structure of a lattice. The compositional and structural complexity of such nanosized systems offers many degrees of freedom for tuning their catalytic properties. The size and species distribution of metallic inclusions within zeolite templates has been shown to affect the catalytic activity of the sample . In this work the optical response of noble metal nano-particles supported on different types of zeolites are studied theoretical and experimentally. The absorbance spectra of Cu, Ag and Au nanoparticles supported on mordenite, β-zeolite, Na/Y and H/Y zeolites are analyzed. Spectra for pre-exchanged Au-Cu/Na/Y, Au-Ni/Na/Y and Au-Fe/Na/Y are also studied.

A simple effective medium approach (Maxwell-Garnett) is used to obtain a theoretical complex effective dielectric function of the composite and to asses the sensibility of the plasmon resonance to the parameters of the system. The knowledge of these properties can hopefully be applied to the development of optical tools to monitor the synthetic path and aid in the development of controlled synthesis of catalytic materials with predetermined properties.

9163-93, Session PWed

Controlling light with the near-field interference

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Young's double slit experiment is the most frequently used tool for demonstration of the interference principle. Key components for interference pattern creation are both temporal coherence of an excitation source and phase accumulation, undertaken via different trajectories (two slits). However, these fundamental requirements could be relaxed, if the vectorial nature of both excitation source and detection object is introduced. Vectorial coupling via near-field interaction could remove the fundamental requirement on the coherent propagating phase lag. Recently, this concept was proposed and experimentally demonstrated in several experiments [1,2]. These results will be presented at this talk.

The effect of near-field interference was demonstrated with the help of a single source of radiation coupled to a transverse magnetic mode (having vectorial structure of electromagnetic field) of a plasmonic waveguide. It was shown that an elliptically polarized dipole produces destructive or constructive interference in opposite directions and, as a result, excites propagating modes with a controlled directionality of propagation.

Furthermore, we exploited the scalability of optical phenomena to radio waves in order to demonstrate the effect of the near field interference with locally excited emitters. In particular, we show that a circularly polarized emitter (classical antenna in this case) near an anisotropic hyperbolic metamaterial slab will unidirectionally excite extraordinary transverse-magnetic modes in the sample. The direction of the excitation is controlled by the circular dipole handedness. The effect has been demonstrated in the RF regime with a hyperbolic metamaterial based on lumped circuit elements.

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9163-94, Session PWed

Dynamic optical properties of amorphous diamond like carbon nanocomposite films doped with Cu and Ag nanoparticles

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Optical response of different transparent host matrixes embedded with noble metal nanoparticles is dramatically enriched by surface plasmons (SP) that enhance electromagnetic field in the proximity of the metal-dielectric interface. As a result, the optical properties of nanocomposite can be tuned by varying size, shape and packing density of the particles and by changing the particle-matrix interface. The investigation of electron dynamics and energy relaxation processes in noble metal nanoparticles upon ultrafast excitations by femtosecond laser pulses enables to understand the origin and the enhancement mechanism of the nonlinear optical properties for metal-dielectric nanocomposites.

In the current work we present studies on optical properties of diamond like carbon (DLC) (amorphous nanocomposite consisting of the sp2 graphite-like bonded carbon nanoclusters embedded into the sp3 bonded carbon) matrix containing silver and copper nanoparticles. Thin DLC nanocomposite films were synthesized employing unbalanced magnetron sputtering of metal targets with argon ions in acetylene gas atmosphere. The nanoparticle size distribution was analyzed employing scanning electron and atomic force microscopy and image processing software. Chemical composition of the films was determined employing energy dispersive x-ray analysis. The steady-state optical response of such nanocomposites enriched by SPs due to different metal content was analyzed employing UV-VIS-NIR spectrometer. Transient absorption measurements were obtained employing Yb:KGW femtosecond laser spectroscopic system (HARPIA, Light Conversion Ltd.). Steady-state and kinetic spectroscopy measurements were related to the metal filler concentration, nanoparticles size distribution and surface enhancement of Raman signal.

9163-95, Session PWed

Metal-all-around nitride semiconductor plasmonic nanolasers

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Plasmonic nanolasers based on subwavelength-sized metal-oxide-semiconductor (MOS) structures have received much interest due to their capability to break the optical diffraction limit. Recently, epitaxial Ag films have been successfully utilized to fabricate low-loss MOS plasmonic cavities for low-threshold, continuous-wave (CW) operation of plasmonic nanolasers< sup>1< /sup>. However, such lasers are limited by the extensive size of metal film and the maximum achievable output power. Here, we report on the demonstration of high CW output power metal-all-around plasmonic nanolasers based on an MOS core-shell nanorod structure. The achieved device feature sizes are comparable with that of state-of-the-art nanowire transistors developed for nanoelectronics.

In this work, we have demonstrated a low CW lasing threshold (~100 W/cm< sup>2< /sup>) for the gold-all-around blue (440 nm) nanolaser operated at cryogenic temperature. Especially, no emission efficiency droop was observed even at a pump power density as high as 100 kW/cm< sup>2< /sup> for a single nanorod laser. Because of the metal-all-around structure, the lasing peaks showed sharp spectral lines with the same full width at half maximum and linearly increased lasing intensity over a wide range of optical pumping intensity (about three orders of magnitude). The availability of high-power, ultrasmall plasmonic nanolasers can open the way for a wide range of on-chip plasmonic applications.

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9163-96, Session PWed

Tunable plasmonic metamaterials composed of colloidal gold(core)/silver(shell) nanoparticles

Meng-Hsien Lin, National Tsing Hua Univ. (Taiwan)

Owing to the technical difficulty of top-down nanofabrication, most of demonstrated metamaterials have been limited in spectral range and sample size. Here, we experimentally and theoretically demonstrate a new approach for fabricating wafer-scale plasmonic metamaterials using the tunable plasmonic response from self-assembled colloidal Au(core)/Ag(shell) nanoparticle arrays. We show that this bottom-up process can be used to accurately fabricate plasmonic metamaterials with tunable plasmonic resonant frequencies. In particular, by controlling the core-shell ratio of the Au(core)/Ag(shell) nanoparticles, we can create broadband tunable plasmonic metamaterial in that spectral regions that cannot be achieved alone with Au and Ag nanoparticles.

In this work, we utilized colloidal Au(core)/Ag(shell) nanoparticles with varying dimensions (particle diameter: 5.5, 6.5, 7.5, and 9.5 nm; core diameter: 3.5, 4.5, 5.5, and 7.5 nm) to form two-dimensional (2D), close-packed nanoparticle superlattices on quartz substrates for optical absorption measurements. A clear and tunable red shift was observed as we increased the core size from 3.5 to 7.5 nm. We also found that the dispersed Au(core)/Ag(shell) nanoparticles exhibit almost identical absorption spectra, which are independent of their sizes, indicating that the change of shell and core dimensions do not significantly affect the absorption properties of dispersed nanoparticles in this size range. However, for the cases of strongly coupled nanoparticle superlattices, minute changes in the core-shell ratio can greatly impact the collective surface plasmon resonance. By using an effective medium model, we can accurately simulate the plasmonic absorption properties for these 2D superlattices, enabling fabrication of designable plasmonic metamaterials in a wide spectrum.

9163-97, Session PWed

Plasmonic influence on the up-conversion luminescence in $NaYF_4$:Er^{3+}/Yb^{3+} nanocrystals

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In this work we study the energy transfer from nanocrystals to conjugated polymer poly(3-hexylthiophene) (P3HT), which is one of the most commonly used building blocks in bulk heterojunction solar cell architectures. It plays a role in absorbing photons and transferring them efficiently to electron acceptors, where charge separation takes place. By coupling nanocrystals, whose optical properties can be tuned over broad spectral range, it should be possible to extend and/or enhance the absorption of such a hybrid nanostructure. On the other hand, shifting the absorption and emission of the nanocrystals by changing their size or chemical composition, can yield important observations regarding the mechanisms of the energy transfer itself.

The nanostructure, in which nanocrystals were mixed directly into the P3HT layer, was studied by means of high-resolution fluorescence microscopy, both in continuous-wave and time-resolved modes. The experimental setup allows to probe the optical properties at single nanocrystal level.

We find that the emission of P3HT increases significantly by approximately 10-fold when nanocrystals are placed in the layer. This increase is accompanied with increase of fluorescence life-time of P3HT emission. On the other hand, the lifetime of nanocrystals emission gets shorter. These results indicate efficient energy transfer from the nanocrystals to the P3HT layer. We estimate the efficiency of this process to be in the range of 50%.

We anticipate that introducing plasmonically active nanoparticles in such a structure should result in further improvement of the optical, absorption in particular, properties of this system.

9163-98, Session PWed

Using remote excitation-surface enhanced Raman scattering (RE-SERS) to study the influence of nanoparticle properties on hot-spots and spectra

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Surface Enhanced Raman Spectroscopy (SERS) is a promising technique for biochemical imaging and sensing. The SERS enhancement factor can go up to 10 to the 14. The highest enhancements are obtained at hot-spots in the nanogap between nanoparticles (NPs). A challenge of SERS is the generation and control of position of hot-spots. Further, the hot-spots with the sample is exposed to a diffraction limited focal spot of the excitation beam. This leads to larger background signals and decrease in contrast between unenhanced Raman and SERS. A nanowire/nanoparticle system is proposed as potential probe. By using the propagating Surface Plasmon Polaritons on a silver nanowire, spatial confinement and transport of the light can be obtained. Light focused at the end of a nanowire (30µm) can excite SERS hot-spots between the nanowire and nanoparticle micrometers away from the focus (RE-SERS) The spectra obtained at these hot-spots during remote excitation show very little background compared to direct excitation. However, due to the dispersion relation mismatch, the coupling efficiency of light to SPPs at the end of the wire is very low. Second, the laser focus is much larger than the nanowire, precise control of laser focus position is needed. By attaching a nanoparticle at the end, the in- and out-coupling light efficiency is enhanced compared to a free nanowire under the same conditions. In this research, we investigated the influence of shape, size and type of the metal of the attached particle in order to obtain a highly efficient in-coupling, and therefore higher quality RE-SERS spectra.

9163-99, Session PWed

Emergence of same-sign super-chiral electromagnetic fields in chiral clusters of achiral plasmonic particles

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We report emergence of same-sign super-chiral electromagnetic fields in certain chiral geometry of a cluster of achiral plasmonic nano-particles. Until recently it was believed that circularly polarized light possesses highest possible chirality. The pioneering work by Tang and Cohen introduced the concept of super-chiral fields, the chirality of which exceeds that of circularly polarized light by orders of magnitude. These so-called super-chiral fields can be created in the near field of resonant plasmonic nano-particles. The most prominent application of super-chiral fields is deemed to be in enhancing the signal in Circular Dichroism Spectroscopy. CD spectroscopy measures the difference in transmission of differently polarized circular light from chiral biomolecules. However there are obstacles in this implementation. If the plasmonic structure is achiral the enhanced chirality in its near-field will change sign alternatively such that the integrated chirality surrounding the plasmonic particle yields zero. One way to alleviate this problem is to fabricate geometrical chiral structures such as Gammadions and G shaped wheels. However due to fabrication resolutions the big size of these structures shifts the plasmonic resonance frequencies to far-red and near-infrared regions which are far from the desired range of UV-Vis where most of molecular electronic transitions occur. We have observed that certain chiral geometry of achiral silver nano-spheres creates localized super-chiral hot spots with uniform sign of chirality. Since the plasmonic resonance of the constituent silver nano-spheres occurs near molecular transition frequencies this can pave the way to obtain ultra-enhanced interactions between chiral biomolecules and the plasmonic structures.

9163-100, Session PWed

Surface plasmon amplification in Ag/InGaAsP hybrid nano-structures

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We report on experimental and theoretical study for surface plasmon (SP) amplification by stimulated emission in Ag-InGaAsP hybrid nano-structures. For demonstrating efficient SP amplification at telecommunication frequencies, the structure of our device is the asymmetric slab waveguide, which is composed of three layers, with metallic 1D nano grating at the top layer, 700 nm thick InGaAsP semiconductor core as the middle layer, and InP substrate as the bottom layer. The spectral position of SP resonance can be controlled by adjusting of the slit period and fill factor, and the metal slit array has a fill factor of 0.3 ~ 0.7 and period of 330 ~ 460 nm. The normal-incidence transmission spectrum was measured in the near-infrared region. For slit period of 420 nm, transmission dip is appeared at wavelength of 1,440 nm. By comparing experimental results with the computational simulation, it was revealed that spectral dip in transmission spectrum has appeared due to the resonant excitation of the SP mode.

By the optical pumping, enormous carriers are created in the semiconductor gain medium, and the propagating SPs in the interface between the Ag slits and InGaAsP semiconductor can be amplified by the stimulated emission process in the complete compensation of the SP propagating loss. The amount of SP amplification depends on the gain spectrum in the InGaAsP, which can be controlled by adjusting the pumping power and temperature. The observed SP amplification can be applied to elements of metamaterial with compensated propagating loss, ultra-miniaturized energy device and ultrafast nano amplifier.

9163-101, Session PWed

Background-suppressed surface-enhanced molecular detection by metamaterial infrared absorber

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A background-suppressed surface-enhanced molecular detection technique is experimentally demonstrated by utilizing the resonant coupling of plasmonic modes of a metamaterial absorber and infrared (IR) vibrational modes of a self-assembled monolayer (SAM). IR absorption spectroscopy of molecular vibrations is of importance in material/medical science and security detection, since it provides essential information of the molecular structure, composition, and orientation. For direct (far-field) detection of extremely small amounts of molecules, surface enhanced IR absorption (SEIRA) has been extensively studied to dramatically improve the sensitivity by several orders of magnitude. Here, we demonstrate low-background resonant SEIRA by using the metamaterial IR absorber that offers significant background suppression as well as plasmonic enhancement. The fabricated metamaterial consisted of 1D array of Au micro-ribbons on a thick Au film separated by an MgF2 gap layer. The surface structures were designed to exhibit an anomalous IR absorption at ~ 3000 cm-1, which spectrally overlapped with C-H stretching vibrational modes. 16-Mercaptohexadecanoic acid (16-MHDA) was used as a test molecule, which formed a 2-nm thick SAM with their thiol head-group chemisorbed on the Au surface. In the FTIR measurements, the symmetric and asymmetric C-H stretching modes were clearly observed as reflection peaks within a broad plasmonic absorption of the metamaterial. The corresponding numerical simulation well reproduced the experimental results, revealing that a Fano-like anti-resonance arose from the resonant coupling between the plasmonic metamaterial and molecular vibrations. Our metamaterial approach may open up new avenues for further lowering the detection limit of direct IR vibrational spectroscopy.

9163-102, Session PWed

Observation of optical domino modes in arrays of non-resonant plasmonic nanoantennas

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Domino modes are highly-confined collective modes that were first predicted for a periodic arrangement of metallic parallelepipeds in far-infrared region [1]. The main feature of domino modes is the advantageous distribution of the local electric field, which is concentrated between metallic elements (hot spots), while its penetration depth in metal is much smaller than the skin-depth. Therefore, arrays of non-resonant plasmonic nanoantennas exhibiting domino modes can be employed as broadband light trapping coatings for thin-film solar cells [2]. However, until now in the excitation of such modes was demonstrated only in numerical simulations.

Here, we for the first time demonstrate experimentally the excitation of optical domino modes in arrays of non-resonant plasmonic nanoantennas [2]. We characterize the nanoantenna arrays produced by means of electron beam lithography both experimentally using an aperture-type near-field scanning optical microscope and numerically. To associate the calculated field components with measured near-field signal we use the approach based on optical reciprocity theorem [3,4]. Good agreement between experimental and numerical near-field patterns allows us to interpret the observed near-field modes as domino modes.

The proof of domino modes concept for plasmonic arrays of nanoantennas in the visible spectral region opens new pathways for development of low-absorptive structures for effective focusing of light at the nanoscale.

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9163-103, Session PWed

The contribution of plasmon-enhanced photoluminescence to the SERS background

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Although the surface-enhanced Raman scattering (SERS) effect was discovered almost 40 years ago, the broad continuum emission, called the SERS background, that accompanies the Raman bands remains poorly understood. Several models have been reported to explain the SERS background based on inelastic scattering, adsorbate luminescence, plasmon-enhanced fluorescence, and image-molecule mediated coupling in the metal. Photoluminescence (PL) from noble metals is also identified as an important component of the SERS background.

We present measurements of plasmon-enhanced PL, in combination with SERS measurements of benzenethiol self-assembled monolayers, from gold nanowire array (Au-NW) plasmonic surfaces. Measurements from flat as-deposited polycrystalline gold layers show two weak PL emissions at E1~1.9 eV and E2~2.2 eV using laser excitation wavelengths (energies) 632.8 nm (1.96 eV) and 532 nm (2.33 eV), respectively. Emission energies E1 and E2 are attributed to interband transitions near the X and L symmetry points of the Au lattice, respectively. Similar measurements of Au-NW surfaces show the same two emission energies, however, the PL efficiency is significantly increased ~100-200? by tuning the surface plasmon resonance energy close to PL emission energy. SERS measurements of benzenethiol on the Au-NW surfaces reveal that the background shape and peak emission energy are very similar to the measured plasmon-enhanced PL characteristics. Furthermore, the background and PL amplitudes both increase approximately linearly with increased laser excitation power. Our observations indicate that PL is the main contributor the SERS background on Au substrates.

9163-104, Session PWed

Visible light responsive TiO2 photoanodes based on plasmonic meta-structures

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Ever since Fujishima and Honda have reported the photoelectrochemical water splitting by using a titanium oxide in 1972, many researchers has intensively studied the water splitting using semiconductor photoelectrodes such as Fe2O3, TiO2 etc. Although TiO2 shows good reliability with low cost, but the photocatalytic efficiency is still low because of the low light absorption in the visible range. Recently reported, surface plasmon resonance to boost visible light absorption of TiO2, and enhance the hydrogen production of photochemical cell. Here, we report the simple fabrication method of the meta-structured photoanodes for highly-efficient photoelectrochemical cell based on the TiO2 film and Au nanoparticles. The anode consists of Au layer (100 nm), TiO2 film (10 ~ 50 nm), and Au nanoparticles on TiO2 film. Compared with pure TiO2 film, the meta-structured film shows the enhanced visible-light absorption, resulting in the 6 times improvement in the photocurrent. It is ascribed to the the plasmon resonance energy of meta-structure transfer in the TiO2 photocatalyst. We also report the effect of the light absorption by the TiO2 thickness and the Au nanoparticles size on the photocatalytic efficiency.

9163-105, Session PWed

Coherence changes of partially coherent beams in transmission through subwavelength metallic gratings

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Since the discovery of the extraordinary light transmission through a metallic film with subwavelength holes, the transmission resonances of electromagnetic fields incident on periodic slit and hole arrays have been widely studied. It has been shown that it is possible to tailor the spectral transmission properties of the metallic subwavelength structures by varying their geometrical parameters. While there are fewer studies considering the influence of similar structures on the coherence properties of electromagnetic fields, the effect of surface plasmons on field correlations between specific points has been considered in the case of finite slit and hole arrays in metallic films.

In this work we theoretically study the coherence changes induced in periodic subwavelength metallic gratings with narrow linear slits using rigorous numerical simulations based on the Fourier modal method and the coherent mode representation of partially coherent fields. The relation of the grating parameters to the effective degree of coherence of the transmitted field is studied by the numerical simulations and the changes in the coherence functions are illustrated for a Gaussian Schell-model (GSM) beam.

Our numerical results show that by choosing suitable parameters for the grating, the degree of coherence of the beam can be significantly

increased. The coherence properties directly affect, e.g., the propagation characteristics of electromagnetic fields and the novel possibilities to flexibly control them with nanophotonic components could thus be valuable for many types of applications.

9163-106, Session PWed

Super long-range surface plasmons in a silver nano-slab waveguide

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A metal in plasmonic waveguides introduces high propagation losses, resulting in the limitation of application range. Recently, long-range SPPs (LRSPs) with extremely low losses have been studied as key elements for important applications. Regarding slab- shaped waveguide, we have already reported in theory that the smaller waveguide width made the propagation length longer. Here, we experimentally demonstrate the increase of LRSP propagation length in a slab-shaped silver waveguide as the width decreases. According to the calculation, it is found that the propagation losses can be significantly reduced when the waveguide width becomes shorter than the wavelength; we named this mode "super LRSPs". For the experimental demonstration of super LRSPs, we fabricated slab-shaped waveguides by FIB milling. The waveguide consists of a slab-shaped silver film embedded between SiO2 and index-matched polymer. Input and output couplers are defined on the edge of each waveguide to in- and out-couple SPPs. I measured the intensity from the output coupler as a function of the waveguide length. From a simple exponential fit to data, a SPP propagation length of 43.1 μm is extracted, while calculated one is 42.1μm. It means that we successfully demonstrated the propagation property of the fabricated waveguide. In addition, the increase of propagation length will be discussed for subwavelength width in the waveguide.

9163-107, Session PWed

Optical and structural properties of graphene oxide-noble metal bilayers

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Graphene Oxide – metal bilayers are appealing nanostructures in many research fields: biosensors based on Graphene Oxide – gold stack have been recently used for Surface Plasmon Resonance equipment devoted to detection of chemical processes, similar and more complex coatings are also intriguing for development of optical elements in the EUV – UV spectral range. A good knowledge of the samples is required for the proper use because unexpected properties often occur when things arrange on a small scale. The samples have been prepared by tailoring the process according to the needs. We present their full characterization in terms of optical responses and surface and physical properties. The specimens have been observed by Optical Microscope and Atomic Force Microscope to identify flakes and island on the metal. Near Edge X – Ray Absorption Fine Structure spectroscopy has been used to characterize the electronic states, the orientation and the intramolecular bond lengths of the molecules on the surface.

9163-108, Session PWed

Photothermal reshaping of single gold nanorods below melting point driven by surface diffusion

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The use of gold nanorods has become pervasive in many recent technological advancements, with some of the most prominent applications including sensing, photovoltaics, biolabelling and cancer therapy [1, 2]. Gold nanorod stability is vital for preserving the LSPR and the success of these applications. However, instability of the shape during laser exposure has been reported by many and reshaping of nanorods was observed to occur at temperatures far below the bulk or surface melting points [3]. Here, we report a systematic study on photothermal reshaping behaviour of gold nanorods with varying aspect ratios, and show that the behaviour is largely dependent on aspect ratio and has less obvious relationship with bulk or surface melting points. From this result we infer that the curvature-driven surface diffusion plays more important role in photothermal reshaping process than previously thought and need to be considered together with other melting processes. Previously observed low temperature reshaping of gold nanorods at 100-200 degrees Celsius can be well explained with surface diffusion, without invoking the concept of low melting point.

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[2] Durr, N. J., et al. (2007). Nano Letters 7(4): 941-945.

[3] Petrova, H., et al. (2006). Physical Chemistry Chemical Physics 8(7): 814-821.

9163-109, Session PWed

Plasmonic response of different metals for specific applications

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Each metal presents different characteristics when used in a surface plasmon resonance (SPR) experiment. These include the shape of the SPR figure, the wavelength of better operation, the tendency to oxidize, the sensitivity to environmental changes, the range of refractive indices detectable and the capability of binding to specific targets or analytes.

When choosing the metal for our SPR experiment all of these characteristics have to be taken into account.

We investigate the behavior of different metals comparing their characteristics to gold. We deeply investigate both theoretically and experimentally the behavior of palladium. This metal leads to an inverted curve with a maximum of reflected intensity instead of a minimum. In fact, in this case we speak of Inverted Surface Plasmon Resonance (ISPR). Aluminum and copper have also been considered because of their potentiality in specific applications.

9163-110, Session PWed

High resolution characterization of plasmon resonances in silver nanostructures

Edson P. Bellido, David Rossoud, Gianluigi A. Botton, McMaster Univ. (Canada)

In order to study surface plasmon resonances (SPR) at the nanoscale, a characterization technique providing high spatial and energy resolution

is required. Energy loss spectroscopy (EELS) in a scanning transmission electron microscope (STEM) is one of the best techniques for imaging SPR, because the STEM can reach the ultimate spatial resolution, thanks to advancements in electron sources and electron optics. However, EELS has been limited to frequencies in the visible range and higher; mainly because the high intensity of the zero loss peak (ZLP) tail compared with low loss signal intensity. In order to reduce the intensity of the ZLP tail we need to improve the energy resolution of the EELS system.

In this work, we use electron beam lithography to fabricate silver nanorods and nano-squares on silicon nitride membranes. We acquire energy-filtered maps of SPR modes using a state of the art STEM/TEM system, obtaining an energy resolution of 74±5meV. To further increase the energy resolution and reduce the contribution of the ZLP, we apply the iterative Richardson-Lucy (RL) deconvolution. With this method, we obtain a record effective energy resolution of 30 meV after 50 iterations, and an effective resolution of 10 meV after 500 iterations for spectral features below 1 eV energy loss. We extract high-resolution images and energy-filtered maps of SPR of a silver nanorod at energies down to 0.25 eV, corresponding to the mid-infrared region on the electromagnetic spectrum. We were also able to identify hydrid-SPR peaks separated by only 70meV from two silver nano-squares with a gap of 100nm between them.

9163-111, Session PWed

Asymmetric gold nanoparticle reduction into polydimethylsiloxane thin films

Jeremy Dunklin, Gregory T. Forcherio, Donald K. Roper, Keith Berry Jr., Univ. of Arkansas (United States)

Polymer thin films embedded with plasmonic gold nanoparticles (AuNPs) are of significant interest in biomedicine, optics, photovoltaic, and nanoelectromechanical systems. Thin polydimethylsiloxane (PDMS) films containing 3-7 micron layers of AuNPs that were fabricated with a novel diffusive-reduction synthesis technique attenuated up to 85% of incoming laser light at the plasmon resonance. Rapid diffusive reduction of AuNPs into asymmetric PDMS thin films provided superior optothermal capabilities relative to thicker films in which AuNPs were reduced throughout. A photon-to-heat conversion of up to 3000°C/watt was demonstrated, which represents a 3-230-fold increase over previous AuNP-functionalized systems. Optical attenuation and thermal response increased in proportion to order of magnitude increases in tetrachloroaurate (TCA) solution concentration. Optical and thermoplasmonic responses were observed with and without an adjacent mesh support, which increased attenuation but decreased thermal response. Morphological, optical, and thermoplasmonic properties of asymmetric AuNP-PDMS films varied significantly with diffusive TCA concentration. Gold nanoparticles, networks, and conglomerates were formed via reduction as the amount of dissolved TCA increased across a log10-scale. Increasing TCA concentrations caused polymer surface cratering, leading to a larger effective surface area. This method, utilizing the diffusion of TCA into a single exposed partially cured PDMS interface, could be used to replace expensive lithographic or solution synthesis of plasmon-functionalized systems.

9163-112, Session PWed

Increased upconversion quantum yield in plasmonic structures

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Upconversion processes by which two or more low-energy photons are converted into one higher-energy photon have found widespread applications in drug delivery, bio-imaging and silicon solar-cells. Currently, the main drawback of upconverting materials is their low quantum yield. Nano-patterning can improve the upconversion quantum efficiency through two processes: first, radiation can be absorbed more effectively by appropriately patterned structures that lead to higher local irradiances. Second, the rates of the radiative transitions between selected ionic states within the upconverting material can be altered by judiciously modifying the local density of states.

In this talk we present a theoretical model that analyzes the impact of a plasmonic shield structure on upconversion. We use this model to assess the efficiency of upconverting NaYF4: Tm3+ Yb3+/NaYF4 core-shell nanoparticles when embedded in a polymer matrix and covered by a metallic can-like structure. The simulation combines a rate equation approach for the upconversion processes with finite element models that describe the local absorption within the system and the modification of the local density of states due to plasmonic resonances. We find that as a result of this specific plasmonic structure the upconversion luminescence from near infrared to ultraviolet can be increased by a factor of 8 and the upconversion quantum yield can be improved on average by a factor of 20 compared to the unaided case. The high directivity of the radiation pattern emitted from this plasmonic configuration will be also discussed.

9163-113, Session PWed

Geometric optics of gold nanoparticle-polydimethylsiloxane thin films

Jeremy Dunklin, Gregory T. Forcherio, Donald K. Roper, Univ. of Arkansas (United States)

Interest in the optical properties of plasmonic nanoparticles embedded in transparent polymers is expanding due to potential uses in sustainability, biomedicine, and manufacturing. Geometric optics of polydimethylsiloxane (PDMS) thin films containing uniformly or asymmetrically distributed polydisperse reduced gold nanoparticles (AuNPs) or uniformly distributed monodisperse solution synthesized AuNPs were recently evaluated using a compact linear algebraic sum. Algebraic calculation of geometric transmission, reflection, and attenuation for AuNP-PDMS films provides a simple, workable alternative to effective medium approximations, computationally expensive methods, and fitting of experimental data. Generally, transmission and reflection increased with AuNP isotropy and particle density, as displayed on a novel ternary diagram. Irregular AuNP morphology and size distribution caused optical attenuation from polydisperse films to increase in proportion to log10 increases in gold content, resulting in lower attenuation per gold mass when compared to monodisperse AuNPs. Uniform monodisperse AuNP-PDMS films attenuated light in proportion to gold content, with films attenuating 0.15 fractional units per 0.1 mass-percent AuNPs. Thin layers of concentrated AuNPs attenuated light more efficiently. A 25 micron thick layer of 1.2 mass-percent AuNPs attenuated 0.5 fractional units, the same number as a 130 micron thick 0.6 mass-percent film. Measured optical responses from asymmetric AuNP-PDMS films with an adjacent back-reflector and pairs of uniformly distributed films were predictable within 0.04 units of linear algebraic estimates based on geometric optics. This approach allows for the summative optical responses of a sequence of 2D elements comprising a 3D assembly to be analyzed.

9163-114, Session PWed

Second-order coherence properties of nanoscale coaxial lasers

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Metallic nanolasers belong to an emerging family of lasers that have ultra-small size, low threshold, and excellent thermal dissipation properties. This class of nanolasers can be potentially useful for applications such as

on-chip optical communication, near-field probing, ultra-dense sensing and imaging, as well as quantum information technologies.

Coherent laser emission is characterized by high spectral and spatial coherence. In most lasers, an abrupt linewidth narrowing at threshold is typically considered to be an indication of coherent emission. On the other hand, semiconductor-based nanolasers have lower cavity quality factors, operate at reduced pump levels, and have larger linewidth enhancement factors. These aspects lead to a more gradual transition around threshold, thus making it more difficult to unequivocally determine the onset of lasing.

In this work we present experimental measurements of the second order coherence (g(2)) for sub-wavelength nanolasers based on metallic coaxial cavities. As it is well known, the g(2) factor provides a clear and undisputed indication for coherent radiation. Here we use a Hanbury-Brown-Twiss setup in which the output of the device under study is divided equally by a directional coupler, followed by two single-photon detectors. The detectors' outputs are then collected by a 25 GHz oscilloscope that feeds the data to a computer in which the correlation is performed digitally. Results concerning the coherence properties of these nanolasers, above and below threshold, will be presented in this talk. Our experimental findings confirm that coherent emission can indeed be achieved in this newly emerging type of metallic coaxial nanolasers.

9163-115, Session PWed

Optical conductivity of a two-dimensional electron gas with Rashba and Dresselhaus spin-orbit coupling

Jesus A. Maytorena, Catalina B. Lopez, Elmer M. Cruz, Univ. Nacional Autónoma de México (Mexico)

The tunability of the spin-orbit interaction (SOI) in systems with reduced symmetry through electrical gating has motivated the search for new ways of manipulating electron spins without employing magnetic materials and external magnetic fields.

Here we study the dielectric response of a two-dimensional electron gas with both Rashba and Dresselhaus SOI within the self-consistent field approach. We calculate the optical conductivity and dispersion relations of collective modes and single-particle excitations related to intra- and inter-spin-split subband transitions. The interplay of both types of SO couplings give rise to an anisotropic spin-splitting of the electronic subbands. We find that (i) the SO-induced modification of the intra-subband plasmon is too small for realistic values of the parameters, (ii) the inter-subband plasmon branch of the spectrum lies within the corresponding continuum of single-particle excitations, (iii) this continuum and the plasmon spectrum depends not only on the modulable Rashba parameter but also on the direction of propagation, and (iv) the optical conductivity shows the same anisotropic character as a function of the direction of the applied electric field. This anisotropic response can be explained in terms of the nonisotropic momentum space available for transitions due to the simultaneous presence of Rashba and Dresselhaus SO couplings.It suggests new possibilities of tunning of plasmon propagation and control of the optical response.

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9163-116, Session PWed

Nonlinear plasmonics for nanoscale light manipulation and imaging

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Plasmonic nanostructures gave a new boost to the development of nonlinear optics via extreme levels of local field enhancement. Furthermore, metal producing them can also serve as a strong nonlinear source itself, which can be rigorously demonstrated with the help of the hydrodynamic model for conduction band electrons. This leads to a number of both intriguing and practically promising phenomena, which will be reported in our presentation. First, it will be addressed the dynamics of nonlinearly coupled localized plasmon resonances in metal nanoparticles, revealing the role of symmetries in their interaction [1]. The distinctive result of the theory is that the second harmonic generation efficiency, predominately originating from surface nonlinearity, is proportional to the ratio between particle surface area and volume, which emphasizes the significant benefit of nanostructuring. In further development of the nonlinear plasmonic approach, a novel concept of cascaded surface plasmon polaritons, propagating at the interface between a linear dielectric and a metal, will be presented, showing that the beam propagation can be described by the effective nonlinear Schrodinger equation [2]. These theoretical predictions are supported by the comprehensive numerical model, demonstrating soliton formation in an explicit way in the regime of realistic propagation losses.

[1]. P. Ginzburg et al., Phys. Rev. B 86, 085422 (2012).

[2]. P. Ginzburg et al., New J. Phys. 15, 013031 (2013).

9163-117, Session PWed

Plasmon-mediated photo-reactions on gold and silver nanostructures

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We report on our work to use plasmonic enhancement to selectively induce photochemical reactions at the hotspots in plasmonic nanostructures. This can be used to modify the properties of the surface at the hotspot, with the goal of inducing self-assembly of well-defined nanostructures. For example, metal spheres can be illuminated by polarized light, causing preferential photocleavage of ligands bound to opposite poles, onto which other particles can then be assembled, forming dumbbells aligned with the polarization.

We demonstrate than in the case of silver, the interaction with the plasmon mode has a catalytic effect on o-nitrobenzyl-based photocleavable ligands bound to the metal. This group normally requires energetic UV photons to undergo a photoreaction, but the silver sensitizes them to visible light of wavelengths near 550 nm, a wavelength to which plasmon resonances in silver nanostructures can be readily tuned.

In gold, no such sensitization takes place. Combined with the lower plasmon frequency in gold, this means that selectively induced photoreactions at the hot-spots of gold nanostructures must make use of two-photon absorption. We have therefore investigated the effect of ultra-short visible light pulses on our ligands when bound to gold surfaces. The reaction is activated through a combination of thermal activation and two-photon absorption, while at higher power densities, ligands can be ablated from the surface through breaking of the gold-thiol bond. We will present data on the interplay of these effects as a function of laser power and exposure time, and demonstrate assembly of nanoparticles onto optically patterned surfaces.

9163-118, Session PWed

Field effect frequency-tunable epsilon-near-zero metamaterial in the visible

Georgia T. Papadakis, Howard Lee, Luke Sweatlock, Harry A. Atwater Jr., California Institute of Technology (United States)

The epsilon-near-zero (ENZ) response of matter enables unique optical functions such as tunneling of electromagnetic waves and directive emission. Metamaterials composed of multilayer stacks of metals and dielectrics can constitute effective media with ENZ for a small range of wavelengths that depends on the geometry and materials [1]. However, in previous reports, the ENZ wavelength is fixed at the time of metamaterial fabrication. We demonstrate the design of a tunable ENZ metamaterial based on metal and transparent conductive oxide (TCO) multilayers, using the field effect to tune the permittivity of the TCO across thin gate dielectric layers [2]. Our design consists of a multilayer geometry of two layers of Au, separated by an active layer of indium tin oxide (ITO). The two materials are isolated from each other with Al2O3. Under applied bias between the Au and the ITO, an accumulation layer is formed at the Al2O3-ITO interface. The structure is excited with a TE-polarized plane wave. By obtaining the complex reflection and transmission coefficients of the stack using an analytical transfer matrix model, we retrieve the effective permittivity of the metamaterial, by directly relating the metamaterial response to analytical expressions for the transmission and reflection coefficients of the single-homogeneous layer problem [3]. Our calculations show that tunability of the ENZ wavelength as much as 80 nm is possible in the 400-700 nm wavelength regime for carrier concentration changes up to one order of magnitude, comparable to those obtained experimentally [2].

1. T. Xu et al., Nature 497, 470-474 (2013).

2. E. Feigenbaum et al., 10, 2111-2116 (2010).

3. C. Menzel, et al., Phys. Rev. B 77, 195328 (2008).

9163-119, Session PWed

Localized and non-localized plasmon resonance modes and enhanced optical absorption in patterned metal-insulator-metal nanostructures

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Patterned metal-insulator metal structures have been extensively investigated for enhancing optical absorption in the past several years. The advantage of this type of structures is that the absorption wavelength can be tuned by varying the geometry and size of the plasmonic resonators in the structure. Although it is understood that the localized magnetic plasmon resonance is responsible for the strong optical absorption, non-localized plasmon resonance modes also cause strong optical absorptions in the visible and near infra-red wavelength range. In this work, we fabricated this type of nanostructures with varying size and period of gold nano-disks and systematically investigated localized and non-localized plasmon resonance modes and associated light absorptions. The fabricated device structure consists of a patterned gold nano-disk array on a thin aluminum nitride film deposited on a thick gold film. It is found that strengths of both localized magnetic resonance and non-localized plasmon resonance strongly depend on the size and period of gold nano-disks in the structure. The findings in this work can help design efficient light absorbers in the visible and near infra-red regime for energy harvesting and sensor applications.

9163-120, Session PWed

Roughness induced leakage and visualization of surface plasmon-polaritons

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Plasmonics is a subfield of nanophotonics that is primarily concerned with the manipulation of light at the nanoscale using the properties of propagating and localized surface plasmons. Crucial to the development of practical devices based on Surface Plasmon-Polaritons (SPPs) are the excitation, visualization and detection of these surface-traveling waves. It is well known that the propagation of SPPs is very sensitive to surface features; isolated defects, as well as periodic or random structures can be used for both, launching SPPs, and converting them into volume waves. This latter mechanism can be used for their detection or observation.

In this work we study the propagation of SPPs through a surface with random roughness and search for appropriate parameters to promote their controlled leakage and subsequent observation. A balance must be found between the leakage into volume waves and the propagation length. The roughness also determines the directions of leakage. The visualization of the path followed by the SPPs is then possible by collecting the light scattered by this interaction.

Rough surface samples were fabricated by exposing photoresist covered glass substrates to speckle patterns produced with the blue light of a He-Cd laser (λ=442 nm). The properties of the fabricated surface are determined by the exposure and the statistical properties of the speckle patterns. A thick metallic film of gold or silver was deposited on top of the fabricated photoresist film. Visualization experiments illustrating the scattering of SPPs by surface defects have been carried at two popular wavelengths (633 and 980nm).

9163-121, Session PWed

Localized surface plasmon resonances in transformed spaces

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The quasistatic approximation is useful tool for determining the plasmonic resonances of metallic particles that are much smaller than the wavelength of light. In this limit, the interaction is governed by electrostatics rather than electrodynamics and the field can be determined by solving Laplace's equation with appropriate boundary conditions.

Transformation optics (TO), on the other hand, is an emerging area of optics that provides a methodology for manipulating light in unusual ways. It is based on the fact that Maxwell's equations are form invariant under coordinate transformations. Coordinate transformations in which local angles are preserved, are called conformal mappings. They are particularly attractive because they lead to relatively simple modifications of the governing equations. Laplace's equation, for instance, is invariant under a conformal transformation. Not surprisingly, these techniques have been used to study electromagnetic problems in complex geometries. The usual strategy is to start with a well-understood system and, by applying a conformal mapping, find the solution of a more complex system.

We study the localized surface plasmon resonances of metallic nanoparticles in two geometries connected by a conformal coordinate transformation. The conditions are such that the quasistatic approximation should be valid in the initial space. The electromagnetically equivalent problems are solved in the two spaces with rigorous techniques. For comparison, we also consider the problem under the quasistatic approximation and map the solution to the transformed space. The results show that care should be exercised when applying TO techniques under the quasistatic approximation.

9163-122, Session PWed

Wafer-scale aluminum nano-plasmonics

Matthew C. George, Rumyana Petrova, James Frasier, Eric W. Gardner, MOXTEK, Inc. (United States)

Periodic micro- and nano-structures are gaining traction in diverse areas such as bio-sensing, surface enhanced Raman spectroscopy (SERS), solar cell concentration and antireflection strategies, solid state lighting, as well as in optical filters, metamaterials, integrated micro-optics, and even electrochemical devices. Unfortunately, obtaining a reliable, cost effective, yet flexible manufacturing source for such structures has often been a challenge. Many research groups and companies perform their own lithography and etching or use a foundry to generate such structures, but this typically limits the substrate size to a few square inches and can have large up-front costs for masks and other tooling. In addition, the periodicities of structures readily available from commercial sources are typically limited to several hundred nanometers and larger. Moxtek has addressed some of these challenges by leveraging existing capabilities in wafer-scale patterning of sub-wavelength wire grid polarizers into the fabrication of one- and two-dimensionally periodic plasmonic structures.

This presentation will discuss fabrication, characterization, and optical modeling results for aluminum nano-hole arrays with potential applications in surface plasmon resonance sensing, SERS, and surface-enhanced fluorescence spectroscopy (SEFS). Potential markets include micro-arrays for bio-related assays and trace level chemical detection. In addition, the presentation will review recently-commercialized work on narrow-band, cloaked wire grid polarizers composed of nano-stacked metal and dielectric layers patterned over 200 mm diameter wafers for projection display applications. The stacked sub-wavelength nanowire grid results in a narrow-band reduction in reflectance by a factor of about 20, which can be tuned throughout the visible spectrum for stray light control.

9163-123, Session PWed

The field enhancement and optical sensing in array of almost adjoining metal and dielectric nanorods *(Invited Paper)*

Andrey Ivanov, R&D Co. VICHEL (High- Frequency Systems) (Russian Federation); Alexander N. Shalygin, R&D Co. VICHEL (High-Frequency Systems) (Russian Federation); Andrey N. Lagarkov, Institute for Theoretical and Applied Electromagnetics (Russian Federation); Alexander Vaskin, Moscow Institute of Physics and Technology (Russian Federation); Andrey K. Sarychev, Institute for Theoretical and Applied Electrodynamics (Russian Federation)

The surface plasmon (SP) excitations in the ordered array of nanorods have attracted significant attention in recent years due to numerous potential applications in nanoplasmonics including transmitting and processing optical signals on a scale much smaller than the wavelength.

In our work the plasmonic system consisting of two-dimensional periodic array of nanorods is considered. We use computer simulating as well as exact analytical solution to find reflectance and transmittance from plane composed of nanorods, which have various diameters and inter-particle spacing. As the nanorods approach each other, a series of surface plasmon resonances are excited, which are strongly localized between nanorods due to collective resonances. It is shown that the local electric field is much enhanced in the interparticle gap at the resonance. The reflectance and transmittance have sharp minima and maxima corresponding to the excitation of various SP resonances. The local electric field concentrates at the scale much smaller than the diameter of the rod. The computer simulations are in a good agreement with our analytical theory. The resonance frequencies and field enhancement can be tuned by variation of the shape and arrangement of the nanorods. The system of nanorods that almost touch each other by their generatrices can be used in creating the surface of plasmonic sensors. It is possible to tune resonance frequencies in our system so they correspond to Stokes shifts in an analyte. Therefore we propose very effective SERS sensors to generatrices various substances.

9163-124, Session PWed

Investigation of optical limiting properties of aluminium nanoparticles prepared by laser ablation in different carrier media

K. Mayank S. Sharma, Pranam Prakash, Cochin Univ. of Science & Technology (India) and Univ. of Hyderabad (India)

In this communication, we carried out the systematic investigation of nonlinear absorption and scattering properties of Aluminum nanoparticles (Al NPs) in various polar and non-polar solvents.Al NPs were synthesized with pulsed Nd:YAG laser operated at 1064 nm by ablating Al target in polar and non-polar liquid environment like chloroform, chlorobenzene, toluene, benzene, and carbontetrachloride. Synthesized Al NPs colloids of various solvents differ in appearance and UV-Vis extinction spectra exhibit absorption in the UV region. The characterization of Al NPs performed by Transmission electron microscopy (TEM) studies reveal that NPs are made up of a well crystallized Al inner part (bright zone) embedded with an amorphous metal Al shell (dark region). Growth, aggregation, and precipitation mechanisms which influence the optical properties and stability of NPs are found to be related to the dipole moment of the surrounding liquid environment. The nonlinear absorption and scattering studies are performed by open aperture Z-scan technique with 532 nm under nanosecond pulse excitation. The Z-scan measurements are fitted theoretically to estimate both two-photon absorption (TPA) and nonlinear scattering (NLS) coefficients. In polar solvents like chlorobenzene, chloroform synthesized Al NPs exhibited higher TPA, NLS coefficient values, and lower optical limiting threshold values in comparison with partially polar solvent like toluene and non-polar solvents like benzene and carbontetrachloride. These results indicate the potential use of Al NPs as a versatile optical limiting material.

9163-125, Session PWed

Exciton-plasmon interaction in core/shell spherical nanoparticles

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Optical excitation in Fluorophore-Metall core/shell nanostructures can lead to energy transfer or to charge transfer between layers, these processes can proceed from fluorophore to metall particle and vice versa. Depending on the spatial arrangement of the layers in the structure and photophysical properties of core/shell components, linear and nonlinear properties can change dramatically. One of the most important reasons for mentioned above changes is to excite oscillations of an electron density in metallic structures, such as gold nanoparticles. So localized plasmons are excited in laser field. The superposition of plasmonic modes defines a near-field distribution of intensity. Fluorophores placed near the gold nanoparticle are excited by plasmon-generating near-field. It is shown that the intensity of the field near the gold nanoparticle is more one order of magnitude higher than the incident field intensity. High intensity in the near field leads to increase the probabilities of fluorophore electronic excited state transition.

However, the excited states relaxation rate of fluorophores placed near gold nanoparticles is also undergoing significant changes. The phenomenon of change in the decay rate of fluorophores in a heterogeneous environment is known as Purcell effect. Changes in the excited states decay rate by Purcell effect give changes in the quantum yield of fluorophore luminescence. Thus, in the proposed model a treatment of the processes of absorption, scattering and luminescence in multilayered spherical nanostructures is reduced to solve the problem of electromagnetic waves scattering on a multilayered sphere, finding the field distribution in the layer of fluorophore, followed by presentation of fluorophores in the form of a 2-level quantum system and determining the rate of spontaneous decay of these systems in the relevant field near the gold core.

9163-126, Session PWed

Study of plasmonic coupling between InAs quantum dots and ErAs nanoparticles in an epitaxial matrix

Luke J. Bissell, Kurt G. Eyink, Elizabeth H. Steenbergen, Joshua R. Hendrickson, Frank Szmulowicz, Krishnamurthy Mahalingam, Lawrence Grazulis, Daniel Esposito, Andrew Aronow, Jeremy A. Massengale, Madelyn Hill, Air Force Research Lab. (United States)

We have studied the optical emission and absorption characteristics of ErAs semimetal nanoparticles (sMNPs) and InAs quantum dots (QDs). Vertical stacks of ErAs sMNPs and InAs QDs were created by strain-driven self-assembly using solid-source molecular beam epitaxy. The composite structures consisted of 8 periods of a layer of InAs QDs followed by a layer of ErAs sMNPs, each in a GaAs matrix. The spacing between ErAs and InAs layers was varied: 8, 10, 12, and 40 nm. The nominal period was 80 nm; the periods measured by XRD were 83 nm – 89 nm. We correlated changes in the photoluminescence (PL) intensity of these layers with changes in the spacing between ErAs and InAs layers. For samples with 10, 12, and 40 nm spacing, the PL integrated intensity increased with increasing InAs – ErAs layer separation. This could be evidence of plasmonic coupling between the sMNPs and QDs. Using time-resolved PL, we measured the sum kPL = kr + knr of the radiative, kr, and non-radiative, knr, decay rates of the InAs QDs. Our measurements showed that kPL decreased with increasing layer separation. It is likely that both plasmonic enhancement of QD emission, and non-radiative quenching, occurred simultaneously. Preliminary results from our analytical model of the plasmonic coupling in this system show that enhancement of QD absorption by a factor of more than 500 is possible.

9163-127, Session PWed

Tunable sensitivity and wide dynamic range phase detection of multichannel grating-coupled SPR sensor

Wen-Kai Kuo, National Formosa Univ. (Taiwan)

We report a multichannel grating-coupled surface plamson resonance (GCSPR) sensor by utilizing a proposed phase-shift interferometer (PSI) for tuning sensitivity and wide dynamic phase detection. The grating structure of the sensor device was fabricated by nano-imprinting technique and a thin meal film was thermally evaporated onto the grating surface. In our system, a cylindrical lens with focal length of 60 mm to form a V-shaped convergent beam with incident angles ranging from 12 degree to 16 degree. Two liquid-crystal modulators (LCM) able to produce over one wavelength retardation were used to produce five-step phase shift in the PSI system. A low-cost web-camera with 130 Mega pixels was used to capture these phase shift images of the multichannel GCSPR sensor and then the five-step phase-shift reconstruction algorithm can obtain spatial phase-shift information. The phase detection sensitivity can be tuned by rotating a polarizer in front of the web-camera. Experimental result shows that detection range larger than 0.01 RIU and detection sensitivity tuning approximately from 10E-5 to 10E-7 RIU can be obtained in our system. In conclusion, this tunable sensitivity and wide range phase detection functions can provide a more flexible SPR sensor detection method. Moreover, the grating coupled and multichannel scheme can provide low-cost and high throughput detection.

9163-128, Session PWed

Optical properties of magnetic-plasmonic nanoparticle multilayers

Ward Brullot, Thierry Verbiest, Katholieke Univ. Leuven (Belgium)

Magnetic-plasmonic materials are an interesting class of materials for fundamental research into magnetoplasmonics, active plasmonics and plasmon-enhanced nonlinear and magneto-optics and for applications in sensing, optical switching and optical components fabrication. For all these research paths, a thorough knowledge of the optical properties and their origin in the materials is a prerequisite.

Using a recently developed layer-by-layer synthesis method, we fabricated magnetic-plasmonic gold/magnetite, silver/magnetite and gold/magnetite/silver nanoparticle multilayers on glass substrates with bifunctional molecular linkers and measured their optical properties.

Discrete dipole approximation calculations to model the optical properties of such materials starting from single nanoparticles up to multilayers allow us to understand the observed optical features. Distances between nanoparticles, the dielectric environment, the number of adjacent particles, the angle compared to the normal, the multipolar order of excitation and the polarization of the incoming light beam are all relevant parameters. In this contribution, we first analyze the obtained theoretical results and then compare them to the experimental observations.

This comparison provides us with a detailed insight in the build-up of the nanoparticle multilayers a.f.o the number of layers. While scanning force microscopy measurements on samples with a certain number of layers confirm a linear increase of thickness as a function of added layers, the calculated and experimental optical properties show a more nuanced trend. Instead of depositing full consecutive nanoparticles layers, the data indicates that nanoparticles of the added layers fill the holes in previous layers and improve the general quality of the sample.

9163-130, Session PWed

Ultra-broadband polarization manipulation and spin-orbit angular momentum conversion based on dispersion engineered metamaterials

Mingbo Pu, Xiangang Luo, Institute of Optics and Electronics (China)

Geometric phase stemming from spin-orbit angular momentum conversion in the adiabatic change of polarization statesis of great importance in applications such as beam shaping and focusing of light. However, the bandwidth of operation is typically limited in the polarization transformation due to the resonant characteristics of metal-dielectric nanostructures. Here we report the demonstration of ultra-broadband polarization transformation based on the complex dispersion properties of anisotropic metallic nanostructures. A typical bandwidth exceeds one octave is obtained in the optical frequencies. The applicability in broadband beam deflection is also discussed. Also, it is shown that broadband optical vortex can be easily realized. The results show that the proposed method is of great advantage over traditional approaches and may lead to a new degree of light beam manipulation.

9163-131, Session PWed

An ultra-broadband nano-plasmonic reflector with an asymmetric nano-ring resonator

Yuhsin Chang, Chyong-Hua Chen, National Chiao Tung Univ. (Taiwan)

An ultra-broadband plasmonic reflector with an asymmetric nano-ring resonator structure based on metal-insulator-metal (MIM) waveguides is numerically proposed. The input and output waveguides are directly connected to this ring resonator, resulting in the excitation of both clockwise and counter-clockwise traveling modes propagating inside the resonator. As a consequence, two interference phenomena are occurred in this structure: ring resonance and Mach Zehnder interference (MZI). We develop analytical formulations to describe these interference behaviors by using the equivalent circuit model based on the transmission line theory. Subsequently, we adjust the lengths of the ring structure to manipulate the resonant wavelengths of the ring resonance, and then the bandwidth roughly equals to the difference of the first and second resonant wavelengths. In addition, the lengths are chosen such that the wavelength for the transmission minimum of the cosine-like MZI envelope is located between these two resonant wavelengths in order to obtain a flat band. The widths of the structure are modified to diminish the low-transmission ripples by minimizing the load voltage on the output waveguide. An example of the plasmonic reflector with the dimension of 200x522 nm^2 and the bandwidth of 1000 nm is numerically accomplished, and the calculated performance is validated with the simulated results obtained by the two-dimensional finite-difference time domain method. Furthermore, the relation between the bandwidth and the dimension of this structure is investigated, showing that the bandwidth is approximately inversely proportional to the device's size.

9163-132, Session PWed

Design of an active terahertz polarizer based on chiral metamaterial

Xiaoliang Ma, Mingbo Pu, Xiangang Luo, Institute of Optics and Electronics (China)

Metamaterials have got intensive interest in tuning the electromagnetic waves, and present various applications in optical and microwave range. In this paper, we demonstrate an active polarizer operating in Terahertz band based on the concept of chiral metamaterial. Period twisted planar metallic spiral structures are constructed on the tunable substrate, whose dielectric permittivity of the substrate can be tuned with outside stimuli. The unit structure of the metamaterial presents chirality due to the broken symmetric, and has the ability of manipulating the polarization states of the incident wave due to its circular dichroism and optical rotation character. When the dielectric permittivity of the substrate is tuned in the range from 3.25 to 3.85, the metamaterial correspondingly converts the incident linearly polarized wave into left-handed circularly polarized, right-handed circularly polarized wave or its cross polarized wave at the resonance of 40 THz. The active metamaterial can be scaled to higher frequency or to microwave range, and it may have potential applications in polarization detective and sensors.

9163-133, Session PWed

Focusing of surface plasmons with a plasmonic lens

Thanh Phong Vo, James E. Downes, David W. Coutts, Judith M. Dawes, Macquarie Univ. (Australia); Alireza Maleki, Macquarie University (Australia)

We report surface plasmonic focusing properties of plasmonic lenses consisting of sectors of concentric circular gratings with period of 776nm and gap width of 310nm perforated on 30nm-thickness gold film on glass. Those structures were studied experimentally and via numerical simulations (COMSOL Multiphysics) as a function of sector angle and number of concentric rings at wavelength of 700nm. With proper arrangement of each single grating so that the grating period matches the wavelength of the plasmonic modes, the surface plasmons excited by scattering incident light at adjacent gratings are constructively interfered when propagating along the air-gold interface, creating an intense focal spot at the focal plane of the circular gratings. Experiment setup was designed for a backside illumination to maximum reduction of background noise and near-field scanning microscopy (NSOM) was used to measure the near-field intensity of surface plasmon modes at 10nm distance from the air-gold interface to experimentally demonstrate the focusing properties of such structures.

We found that the plasmonic field enhancement can be improved abruptly (orders of magnitude) by adding more concentric rings while maintaining the spot size. In turn, the focal spot size at the focal plane of the plasmonic lens is decreased with increased sector angle: at 20o, the focal spot size is 2.4μm, while >90o sectors focus below the diffraction limit. The focusing properties of these plasmonic lenses were confirmed by exciting the plasmonic lens at different locations, i.e edges of circular grating, and in any case, focal spots always present at focal plane.

9163-134, Session PWed

Dark and bright modes manipulation for plasmon-triggered optical switching

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In the last decade, several efforts have been spent in the study of plasmonic coupled systems, in order to induce hybridization of single plasmonic structure modes [1]. Within this context, particular attention has been recently paid on the possibility to couple conventional bright modes to dark plasmonic oscillations triggered by near-field interaction [2]. As a result of such phenomenon, a Fano resonance appears as a characteristic sharp dip in the scattering spectra [3]. A possible way for hybridizing a plasmonic dark mode relies on the excitation of multipolar modes in complex nano-systems [4]. Instead, a more direct approach exploits the combination of dipolar modes properly arranged, requiring a deeper study of elemental LSP modes [5].

Here we present how a symmetry breaking process applied on a nanoantenna dimer can induce the excitation in far-field of the low-energy eigenmodes supported by the system [6]. Such two plasmonic modes can be considered as a minimum set of elemental modes that can be employed for the generation of dark modes in more complex nano-systems. Finally, a T-shape nanoantenna trimer is presented as a strongly polarization-sensitive device supporting plasmonic Fano resonance. In fact, according to incoming light polarization it is possible to "switch" from a conventional plasmonic resonance (high extinction) to a plasmon-triggered Fano resonance.

A direct consequence of Fano hybridization is the definition of a narrow spectral window in which the transmittance of a system can be abruptly increased. Combining such unique property to ultra-fast plasmonic processes, interesting perspectives can be opened towards all-optical switching for tomorrows photonic devices.

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9163-135, Session PWed

Nonlocal quantum effect on optical scattering form small metallic nanoparticles on multilayer films

Huai-Yi Xie, P. Ching-Hang Chien, Yia-Chung Chang, Academia Sinica (Taiwan)

We have studied optical scattering from nanoparticles on the multilayer films and then demonstrate clustering effect of nanoparticles plays an important role between closely-spaced aggregations. However, if the size of a particle is smaller than 10nm, nonlocal correction of nanoparticles must be included. In this work, we present theoretical formulation to investigate optical scattering from small metallic nanoparticles which has correct nonlocal dielectric function. We use a jellium model to calculate the nonlocal dielectric function quantum mechanically within the random phase approximation (RPA) instead of using a translational invariant function as considered in the hydrodynamics model. Within the frame of quantum-mechanical nonlocal dielectric model, our result reduce to both Drude model and local random phase approximation (LRPA) as derived by Lindhard when the size of the particle is larger then 10nm. Based on this quantum-mechanical nonlocal dielectric function of nanoparticles, we include the substrate effect by using the nonlocal scattering integral equations with the multilayer Green's function. The basis functions inside nanoparticles are taken to be linear combinations of scalar harmonic functions and then use Quasi-Minimal Residual (QMR) iteration to solve the unknown coefficients in the nonlocal scattering equation. We calculate optical fields both inside and outside the nanoparticles. For far-field calculation, we evaluate the principle-order reflection coefficient and obtain the ellisometric parameters, Ψ and Δ, which can be used to compare with spectral ellipsometry experiments. Our numerical results illustrate the importance of nonlocal effect for nanoparticles with diameter less than 10nm and provide a more physical prediction than Kubo's model.

9163-136, Session PWed

Polarizability extraction for rapid computation of Fano resonance in nanoring lattices

Gregory T. Forcherio, Drew DeJarnette, Phillip Blake, Donald K. Roper, Univ. of Arkansas (United States)

Rapid modeling of far-field Fano resonance supported by lattices of complex nanostructures is possible with the coupled dipole approximation (CDA) using point, dipole polarizability extrapolated from a higher order discrete dipole approximation (DDA). Fano resonance in nanostructured metamaterials has been evaluated with CDA for spheroids, for which an analytical form of particle polarizability exists. For complex structures with non-analytic polarizability, such as rings, higher order electrodynamic solutions must be employed at the cost of computation time. Point polarizability is determined from the DDA by summing individual polarizable volume elements from the modeled structure. Extraction of single nanoring polarizability from DDA permitted CDA analysis of nanoring lattices with a 40,000-fold reduction in computational time over 1000 wavelengths. Maxima and minima of predicted Fano resonance energies were within 1% of full volume elements using the DDA. This modeling technique is amenable to other complex nanostructures which exhibit primarily dipolar and/or quadrupolar resonance behavior. Rapid analysis of coupling between plasmons and photon diffraction modes in lattices of nanostructures supports design of plasmonic enhancements in sustainable energy and biomedical devices.

9163-137, Session PWed

Broadband, tunable, lattice plasmon resonances with high quality factors

Yi Hua, Claire Deeb, Northwestern Univ. (United States); Gary P. Wiederrecht, Argonne National Lab. (United States); Teri W. Odom, Northwestern Univ. (United States)

Plasmonic metal nanostructures are important for many applications including optical sensors, subwavelength lasers and nonlinear optics. The short lifetime of optical modes in plasmonic structures, however, limits the optical enhancement that can be achieved. Recently, 2D nanoparticle arrays have been demonstrated to support out-of-plane lattice plasmons with extremely high quality factors. In these structures the resonance can be tuned by controlling the height of the nanoparticles as well as the incident angle of the light. Here we report the observation of the out-of-plane dipolar interaction in an easily fabricated nanostructure – nanogratings. In this new structure, we were able to tune the resonance over an even broader wavelength range by controlling the azimuthal angle of the incident light. By adjusting the orientation of the sample relative to the light, the out-of-plane lattice plasmon mode displays a different quality factor that is associated with the change of the spatial confinement of the optical fields around the grating. By controlling orientation of the grating, we investigated the spatial and spectral coupling between J-aggregated meso-tetra(4-sulfonatophenyl)porphyrin (TSPP) with this subradiant plasmon mode.

9163-139, Session PWed

Computational electromagnetic study of plasmonic effects in interdigital arrays

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Plasmonic nanostructures have been shown to act as optical antennas that enhances optical devices. This study focuses on computational electromagnetic (CEM) analysis of GaAs photodetectors with gold interdigital electrodes. Experiments have shown that the photoresponse of the devices depend greatly on the electrode spacing and the polarization of the incident light. Smaller electrode spacing and transverse polarization give rise to a larger photoresponse. This computational study will simulate the optical properties of these devices to determine what plasmonic properties and optical enhancement these devices may have.

Our model will be solving Maxwell's equations with a finite element method (FEM) algorithm provided by software COMSOL MultiPhysics. The preliminary results gathered from the simulations follow the same trends that were seen in the experimental data collected, that the spectral response increases when the the electrode spacing decreases. Also the simulations show that incident light with the electric field polarized transversely across the electrodes produced a larger photocurrent as compared with longitudinal polarization. This dependency is similar to other plasmonic devices. The simulation results compare well with the experimental data. This work will also model enhancement effects in nanostructure devices with dimensions that are smaller than the current samples to lead the way for future nanoscale devices. By seeing the potential effects that the decreased spacing could have, it opens the door to a new set of devices on a smaller scale, potentially ones with a higher level of enhancement for these devices.

In addition, the precise modeling and understanding of the effects of the parameters provides avenues to optimize the enhancement of these structures making more efficient photodetectors. Similar structures could also potentially be used for enhanced photovoltaics as well.

9163-140, Session PWed

Kerr effect from single gold nanoparticles

Emeric Bergmann, Anthony Maurice, Emmanuel Benichou, Christian Jonin, Pierre-François Brevet, Univ. Claude Bernard Lyon 1 (France)

The optical modulation (or Kerr effect) from a gold metallic nanoparticle has been obtained by the P-Scan method. Commercial colloidal solutions of gold nanoparticles were diluted and dispersed onto a thin glass substrate by spin coating. These nanoparticles were then studied with a tightly focused femtosecond laser beam at the fundamental wavelength of 840 nm and for different incident intensities. The retro-reflected intensity was recorded in far field. Clear deviations from the linear regime was observed and attributed to both nonlinear refraction and nonlinear absorption.

9163-61, Session 15

Transmission characterization and control of metallic nanohole arrays by sub 5 fsec laser light pulses

Kellie Pearce, Ludwig-Maximilians-Univ. München (Germany) and Max-Planck-Institut für Quantenoptik (Germany); Jürgen Schmidt, Christian Späth, Ludwig-Maximilians-Univ. München (Germany); Huaihai Pan, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); Hassan M. Ouacha, Abdallah M. A. Azzeer, King Saud Univ. (Saudi Arabia); Ulf Kleineberg, Ludwig-Maximilians-Univ. München (Germany) and Max-Planck-Institut für Quantenoptik (Germany)

The phenomenon of extraordinary optical transmission (EOT) has generated much theoretical and experimental interest since its discovery 16 years ago . Arrays of subwavelength apertures in ordinarily opaque metal films have demonstrated remarkably high transmission efficiencies, in some cases even exceeding unity when normalised to the holes' areas. This ability has been attributed to the excitation of surface plasmons at the interfaces of the film. Potential applications of such arrays include biological sensing, and integration into novel photonic devices.

Two important factors contributing to EOT are the interactions between individual holes, and the coupling between the two interfaces of the film, which transpire on femtosecond time scales. Additionally, the possibly short lifetimes of the plasmon resonances may limit the use of hole arrays in devices, so understanding the temporal dynamics of EOT is important from both a fundamental and practical standpoint. We perform time-resolved measurements of the transmission through subwavelength hole arrays using sub-5fs laser pulses. An initial pump pulse excites the surface plasmon modes followed by a second, weaker probe pulse. The change in the transmission with varying time delay between the pump and probe pulses is measured. Hole arrays with differing hole spacings, shapes and thicknesses are investigated.

As an outlook, we wish to observe the influence of the carrier envelope phase (CEP) of an ultrashort pulse on EOT, thereby determining the extent to which the transmission can be controlled by the incident electric field.

9163-62, Session 15

Engineering plasmonic interactions in three dimensional nano-structured systems

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Engineering plasmonic interactions in a system of metal nanoparticles can lead to new optical effects of immense technological importance. In particular, the role of geometrical arrangement of the metal nanoparticles (MNPs) can have strong influence on their collective optical response. While the effects of these interactions in one (1D) and two (2D) dimensional systems are reasonably well understood, the realm of 3D systems is much less explored.

When it comes to arranging MNPs in three dimensions, one way is to position them one on top of the other, in a stacking fashion. We used a wafer scale technique, known as Glancing Angle Deposition (GLAD), where we evaporate metallic and dielectric materials alternately at a glancing angle to the underlying substrate. The resultant porous structure consisted of MNPs arranged in a stacking fashion separated by the dielectric material. A trivial extension of this method is to arrange the MNPs in a helical (chiral) fashion, which has been achieved in our experimental system. The chiral arrangement of the MNPs obtained in our experiments shows very large circular dichroism, i.e. it absorbs left and right circularly polarised light by different amounts. In the present paper, we describe the method of fabrication, and how the plasmonic interactions can be engineered to obtain a very large and spectrally wide chiro-optical response across the visible regime. These functionalities may be useful in developing new sensors for chiral molecules such as various proteins, as well as in realising broadband circular polarisers in the visible.

9163-64, Session 15

Charge transfer and quantum coherence in solar cells and artificial light harvesting system *(Invited Paper)*

Christoph Lienau, Carl von Ossietzky Univ. Oldenburg (Germany)

In artificial light harvesting systems the conversion of light into electrical or chemical energy happens on the femtosecond time scale, and is thought to involve the incoherent jump of an electron from the optical absorber to an electron acceptor. Here we investigate the primary dynamics of the photoinduced electronic charge transfer process in two prototypical structures: (i) a carotene-porphyrin-fullerene triad, a prototypical elementary component for an artificial light harvesting system and (ii) a polymer:fullerene blend as a model system for an organic solar cell. Our approach [1] combines coherent femtosecond spectroscopy and first-principles quantum dynamics simulations.

Our experimental and theoretical results provide strong evidence that the driving mechanism of the primary step within the current generation cycle is a quantum-correlated wavelike motion of electrons and nuclei on a timescale of few tens of femtoseconds. We furthermore highlight the fundamental role played by the flexible interface between the light-absorbing chromophore and the charge acceptor in triggering the coherent wavelike electron-hole splitting.

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9163-65, Session 15

Mechanism of plasmon enhanced upconversion processes in $NaYF_4$:Yb^{3+},Er^{3+} nanoparticles

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Rare-earth activated upconversion material is receiving renewed attention for their potential applications in bioimaging and solar energy conversion. To enhance the upconversion efficiency, surface plasmon has been employed but widely varying enhancements from 3-fold to 310-fold have been reported, as the enhancement mechanism awaits clear elucidation.

In this study, we synthesized upconversion nanoparticles (UCNPs) coated with amphiphilic polymer which makes UCNPs water-soluble and negatively charged. Three-layer UCNPs were deposited by polyelectrolyte-mediated layer-by-layer deposition on silver nanograting fabricated by laser interference lithography. The final structures exhibited surface plasmon resonance at 980 nm, the UCNP absorption wavelength.

The green and red photoluminescence intensity of UCNPs on grating was up to 16 and 39 times higher than the UCNPs on flat silver film, respectively. However, under strong excitation, the enhancement factor decreased to 3.1. A thorough analysis of rate equations showed that the enhancement was due entirely to absorption enhancement in the strong excitation regime while it equals (FA*FC)^2 under weak excitation, where FA and FC are enhancement of absorption and Förster energy transfer, respectively. Purcell factor was small and unimportant because the non-radiative decay dominates the relaxation processes. From the experimentally observed enhancements, we concluded enhancement factors of 3.1 and 1.3 for absorption and energy transfer, respectively.

This study clearly elucidates the plasmon enhancement mechanism, allowing the fair comparison between various plasmonic UCNP systems and also the rational design of optimal plasmonic structures.

9163-66, Session 15

Experimental demonstration of plasmonic resonant guided wave network

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Resonant guided wave networks (RGWNs) have been theoretically proposed to function as topological optical networks that can be engineered to have optical functionality such as serving as resonators and color routers [1]. The RGWN concept is quite general, consisting of optically isolated waveguides in a network layout, whereby the isolated waveguides serve to transport energy and information within the network and the waveguide crossings serve to redistribute that information within the network [2]. In this work, we experimentally demonstrate a plasmonic implementation of the RGWN concept by demonstrating that a properly excited 90-degree waveguide crossing of two v-groove channel plasmon polariton (CPP) waveguides operates as an ultra-compact power-splitting element, the key component for the realization of the RGWN concept. By combining these plasmonic power splitters together with the CPP waveguides that comprise them in a network layout, we demonstrate a prototype plasmonic nanocircuit composed of four v-groove waveguides in an evenly spaced 2 x 2 configuration, which functions as a compact optical logic device at telecommunication wavelengths, routing different wavelengths via different on/off combinations to separate transmission ports. The reported logic device exhibits expanded 8-port functionality compared to other photonic crystal/plasmonic add/drop filters, in which only two on/off states are accessible. We also investigate the RGWN using antenna-coupled slot waveguides [3] and examine the coherent resonant effect by reducing the size of resonator to sub-micron range. This work illustrates how ultra-compact plasmonic components can form the platform for next-generation integrated plasmonic circuits, and paves the way for the integration of Si-photonics with sub-wavelength mode volume plasmonic waveguides.

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9163-67, Session 15

Near-field vector analysis of plasmonic structures enhancement on infrared photodetectors

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In this work, we fabricated and compared two complimentary plasmonic structures: the metallic circular disc array and the 2 dimensional subwavelength hole array (2DSHA). The near field electric-field (E-field) vector distributions of the two different plasmonic structures are analyzed. We also investigated the different plasmonic structure enhancements on quantum dots infrared photodetectors (QDIP). To fully ascertain the plasmonic enhancements in QDIPs, it is crucial to understand the E-field vector distributions in the plasmonic enhanced QDIP and identify their contributions. The E-field vertical extension of different plasmonic structures and their overlap with the quantum dot (QD) active regions are also simulated. Our studies indicate that the overlapping of the E-field vectors with the QD active region is critical to improve the QDIP performance. Detailed results and analysis will be discussed in the paper. We believe that the vector field analysis not only advances the knowledge of E-field components in plasmonic structures and their interaction with the QDs, but also provides the design guidance for high performance plasmonic enhanced optoelectronic devices.

9163-68, Session 16

Chirality enables unusual optical force *(Invited Paper)*

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Light can exert radiation pressure on any object it encounters and that resulting optical force can be used to manipulate particles. It is natural to expect that light should push a particle forward. However, our results indicate that an anomalous lateral force can be induced in a direction perpendicular to that of the incident photon momentum if a chiral particle is placed above a substrate that does not break any left-right symmetry. We demonstrate the existence of the lateral force by calculating the optical forces acting on helical gold particles induced by a linearly polarized plane wave. Analytical theory shows that the lateral force emerges from the coupling between structural chirality and the light reflected from the substrate surface. Such coupling induces a sideway force that pushes chiral particles with opposite handedness in opposite directions.

9163-69, Session 16

Polarimetric analysis of the extraordinary optical transmission through subwavelength hole arrays

Oriol Arteaga, Univ. de Barcelona (Spain); Shane Nichols, New York Univ. (United States); Ben Maoz, Gil Markovich, Tel Aviv Univ. (Israel); Bart Kahr, New York Univ. (United States)

This work examines the complete polarimetric response of oblique- and square- lattices of metal subwavelength hole arrays that display extraordinary optical transmission at certain frequencies mediated by the excitation of surface plasmons. The study is based on the analysis of the Mueller scattering matrix measured at normal and oblique incidence for plane wave illumination. At normal incidence the square lattice of nanoholes shows a fully isotropic optical response in which the intensity of transmitted light is insensitive to the incoming polarization. However, the oblique lattice has a marked anisotropic character, which permits some types of polarization to be transmitted more efficiently than others.

Moreover, from the spectroscopic Mueller matrix measurements, it is deduced that the oblique array has a rather strong natural optical activity that is combined with asymmetric (non-reciprocal) transmission of circularly polarized light. A repeated measurement with the sample turned over confirms this effect, which is most likely due to the coupling of the linear optical anisotropies induced by misaligned surface plasmons in the film. At oblique incidence the square lattice also shows asymmetric transmission at non-normal incidence, whenever the plane of incidence does not coincide with a mirror line.

9163-70, Session 16

ZnO as a tuneable metal: new types of surface plasmon polaritons at infrared wavelengths

Sascha Kalusniak, Sergey Sadofev, Fritz Henneberger, Humboldt-Univ. zu Berlin (Germany)

The interaction of metals with electromagnetic radiation gives rise to collective charge excitations called surface plasmon polaritons (SPPs). Though discovered a long time ago, strongly reinforced scientific and practical interest in these coupled light-matter states aroused in recent years building the interdisciplinary field of plasmonics. Fascinating examples involving SPPs are the sub-wavelength control of light, below-diffraction-limit microscopy, radiation hot spots, or biosensing, to name only a few. However, currently available plasmonic functions are still constrained by the limited ability to tailor the SPP's frequency-versus-wavevector dispersion, even when utilizing modern nanofabrication techniques. Here we show that use of the free-electron gas in a heavily doped semiconductor (ZnO:Ga) enables the realisation of almost arbitrarily shaped SPP dispersion curves, not only by tuning of the dielectric function but also by coupling of SPPs in planar multi-layered structures. In particular, by preparing metal/metal-type interfaces, we demonstrate SPPs exhibiting finite frequencies in the long-wavelength limit, in marked contrast to the conventional dielectric/metal SPPs. Moreover, the controlled formation of frequency gaps or, alternatively, opening of otherwise forbidden regions are made possible by an appropriate layer design. The operational spectral range covered by our approach extends from the mid infrared to telecommunication wavelengths (where traditional metals suffer from strong dissipation losses) manifesting thus an enormous technological potential: The existence of finite-frequency long-wavelength SPPs allows for targeting new concepts for nanophotonic lasing. By engineering of the dispersion relations, phase matching can be achieved enabling nonlinear plasmonic processes, like second-harmonic generation, or control of the SPP propagation by adjusting their group velocity. Given the advanced possibilities to structure semiconductors down to the nanometer-length scale, we anticipate novel plasmonic functional elements and devices even beyond the planar setting of our study.

9163-71, Session 16

Enhancement in conversion efficiency of organic photovoltaic devices by plasmonic nanostructure

Wakana Kubo, RIKEN (Japan) and Japan Science and Technology Agency (Japan); Takuo Tanaka, RIKEN (Japan) and Hokkaido Univ. (Japan)

Au nanodot arrays were embedded in an organic photovoltaic device for the purpose of light trapping. Consequently, the photovoltaic device with Au nanodots showed an improvement in conversion efficiency. For discussing its enhancement mechanisms, we examined an induced photon to conversion efficiency of the device with Au nanodots and optical characteristics of Au nanodots. Finally, we found a correlation between plasmon resonance of Au nanodots and an induced photon to conversion efficiency spectrum of the device with Au nanodots.

9163-72, Session 16

Far-field and near-field analysis of gold nanoantennas in Kretschmann configuration

Kuo-Ping Chen, Yi-Hsun Chen, National Chiao Tung Univ. (Taiwan)

Gold nanoantenna arrays with Kretschmann prism coupling configuration are designed as high sensitivity bio-sensor. Comparing to normal incidence of gold nanoantennas, total internal reflection does not only achieve higher near-field enhancement, but also transfer input energy into localized surface plasmon resonance with less impedance mismatch.

In this work, gold nanoantennas are fabricated by E-beam lithography. The transmittance and reflectance spectra are measured in normal incidence and also in Kretschmann prism coupling configuration, which is with BK7 prism and water as surrounding medium. By analyzing the far-field reflectance spectra, in TM polarization, the resonance wavelength is at 780nm in normal incidence but at 690nm when the incidence angle is larger than the critical angle. Not only the resonance wavelength is with 90 nm blue-shift, but also the FWHM is reduced from 165nm to 58nm, which provides the better Q-factor. More interestingly, by analyzing near-field EM wave distributions, the phase of each particle in paired nanoantennas is analyzed in resonance condition. In normal incidence, the resonance of two particles are in phase , but with 180 degree phase difference when the incidence angle is larger than critical angel, which could be indicated to bright mode and dark mode resonances. By applying to bio-sensor application, the figure of merit of gold nanoantennas shows 4.15 times higher by using Kretschmann configuration than the case in normal incidence.

9163-73, Session 17

Near-field, back-action cooling and amplification

Iman Hassani Nia, Hooman Mohseni, Northwestern Univ. (United States)

Plasmonic structures produce well-known enhancement of the near-field optical intensity due to sub-wavelength optical confinement. These properties can produce a significant change of reflection upon small mechanical change of the antenna configuration. We have developed a method based on this enhanced sensitivity for cooling and amplification of a moving mirror. Using finite difference time domain method and standard optomechanical coupled-equation, different regimes of operation such as laser detuning and cavity length were studied to compare the effect of the near-field enhancement with the conventional radiation pressure. Using practical microcavity parameters, we demonstrate significantly higher cooling - or amplification- efficiency for the near-field plasmonic effect compared with that of the radiation pressure. Moreover, the volume of the system is very small. We believe that the significant efficiency improvement and reduced volume due to the proposed near-field effect can make this approach practical for many applications ranging from gravitational wave detection to photonic clocks, high precision accelerometers, atomic force microscopy, laser cooling and parametric amplification. While all existing optomechanical structures rely on the momentum exchange of propagating photons to produce the back-action, we show that utilization of near-field photons might in fact be a much better choice.

9163-74, Session 17

Polarization manipulation with subwavelength nano apertures

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Manipulation and determination of circularly polarization states of light with nanoscale optics form a building block for future telecommunication and biosensing technologies. One potential method is to exploit localized surface plasmon resonances in patterned thin metallic films. Here we demonstrate a compact plasmonic quarter wave plate (PQWP) based upon detuned orthogonal nanoapertures. We also demonstrate a thin circular polarization filter based upon a far field interference of light transmitted through a pair of nanoapertures comprising a planar chiral unit cell.

Our PQWP design consists of an array of asymmetric cross apertures in a 50 nm silver film. The asymmetry in cross arm lengths is tailored to impart a 90° phase difference between orthogonal components of the transmitted field. Full polarization tomography reveals the fabricated array does indeed act as a quarter wave plate.

Our 2D chiral metamaterial based circular polarization filter uses an array of chiral pairs of apertures in a 50 nm Ag film. The apertures are designed si that when illuminated with LHCP light, the transmitted field interferes constructively, whereas RHCP light interferes destructively, leading to an asymmetric transmission of 10%.

9163-75, Session 17

Observation of quantum interference in the plasmonic Hong-Ou-Mandel effect

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Optical signals are increasingly used to transfer and process information, because of their high speed, bandwidth, and propagation distances in transparent optical networks. However, the miniaturization of photonic devices faces a hard block: the diffraction limit. One proposed means to go beyond this limit is to use surface plasmons polaritons (SPPs), charge density waves at the interface between a metal and a dielectric, which can be excited with light, as the carrier of the information. So far, the study of plasmons has been confined to the classical regime, but recently more attention is given to the quantum regime: several interesting devices taking advantage of the large field confinement provided by SPPs have been proposed, such as single photon switches. However, at this stage, little is known about the behavior of SPPs in the quantum regime. In this presentation, we report direct evidence of the bosonic nature of SPPs in a scattering-based beamsplitter, in one of the most simple experiments of quantum optics - done using SPPs instead of photons propagating in air. A parametric down-conversion source is used to produce two indistinguishable photons, each of which is converted into a SPP on a metal-stripe waveguide and then made to interact through a semi-transparent Bragg mirror. In this plasmonic analog of the Hong-Ou-Mandel experiment, we measure a coincidence dip with a visibility of 72%, a key signature that SPPs are bosons and that quantum interference is clearly involved.

9163-76, Session 17

Plasmon hybridization in ITO/Ag core shell nanoarrays

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Metal and metal oxide electrodes play a significant role in many cutting edge applications including photonics, membranes, biological supports, sensing, electrochromics, and in various green technologies, such as, photocatalytics, Li-ion batteries and photovoltaics. There is strong interest in the ability to create one-dimensional nanoscale metal and metal oxide electrode structures that provide high surface area, tunability of the electrode – organic interfaces, and low tortuosity for improved electron / hole transport characteristics. Interest in patterning polymer based nanodevices and creating sub-100 nm metal and transparent conducting oxide (TCO) based nanostructured electrodes (NSEs) has led us to modify the traditional imprint lithography technique to enable synthesis of an array of sub-30 nm diameter polymer nanostructures. In this approach, a hard e-beam lithographed Si or SiC master is used to directly imprint a large area nanopattern onto polyacrylonitrile (PAN) film. The PAN film is then cured at ~ 200 °C to synthesize nanostructures. Large area nanostructured hybrid silver and indium tin oxide (ITO) arrays with feature sizes below 100 nm have been fabricated. The optical and electrical properties of these core shell electrodes including the surface plasmon frequency can be tuned by suitably changing the dielectrics and their dimensions. The surface plasmon wavelength of the nanopillar Ag changes from 650nm to 690nm depending on the dimensions of the pillars. Adding layers of ITO to the structure shifts the resonance wavelength toward the infrared region by an amount depending on the sequence and thickness of the layers in the structure.

9163-77, Session 17

Plasmonic black metals in resonant nanocavities

Mihail Bora, Elaine M. Behymer, Jerald A. Britten, Cindy C. Larson, Allan Chang, Hoang T. Nguyen, Tiziana Conese Bond, Lawrence Livermore National Lab. (United States)

We investigate a plasmonic resonant structure tunable from ultra-violet to near infrared wavelengths with maximum absorbance strength over 95% due to a highly efficient coupling with incident light. Additional harmonics are excited at higher frequencies extending the absorbance range to multiple wavelengths. We propose the concept of a ‘black’ plasmon resonator that exhibits broadband absorbance characteristics by spacing the modes closer through increasing the resonator length and by employing adiabatic plasmonic nano-focusing on the tapered end of the cavity.

Plasmons have a wide range of uses for refractive index based bio-sensing, molecular specific surface enhanced Raman spectroscopy (SERS), improvement of photovoltaic efficiency, and plasmonic laser devices. These applications require high extinction strength of the plasmonic resonances such that near field effects dominate the physical behavior, hence design considerations for optimal structures aim at controlling both the resonant wavelength and the coupling with the incident light. Solar cell efficiency increases through conversion of evanescent plasmon field into excitons have been demonstrated, but these approaches have limited practicality because either they are effective only for narrow spectral and incidence angle ranges or rely on attenuated total internal reflection coupling geometry which is often impractical . Nevertheless, recent studies that incorporate metallic nanostructures with strong coupling of incident light and broad spectral and angular coverage can provide a path for more efficient photovoltaics by means of plasmon-exciton conversion. Herein we present a structure that addresses the broadband absorbance requirement for plasmonic photovoltaics.

9163-78, Session 18

Quantum-coherence-enhanced plasmonic nanostructures for near-field spectroscopy and control

Dmitri V. Voronine, Texas A&M Univ. (United States)

Quantum coherence [1] has previously been used to enhance nonlinear optical signals, for example, in coherent Raman scattering. Near field enhancement from plasmonic nanostructures can also dramatically improve Raman signals. We investigate quantum coherence effects in plasmonic nanostructures coupled to gain media to enhance

the efficiency of surface plasmon generation [2]. We simulate the dependence of surface-enhanced coherent anti-Stokes Raman scattering (SECARS) spectra on the position and line width of the surface plasmon resonance, and attribute small (and even negative) enhancement factors to local destructive interference. We report measurements of nanoscale phase effects in SECARS of pyridazine on gold nanoparticle aggregates, and propose strategies to increase enhancement factors towards theoretical predictions. The new quantum-coherence-enhanced nanostructures can be used for a variety of spectroscopic applications.

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9163-79, Session 18

RF-based optical patch antenna design and analysis

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Optical antennas help surpass the diffraction limit, hence enable visualization, manipulation and control of light-matter interaction at subwavelength scale. These nano-scale antennas promise a breakthrough in the areas of energy harvesting, information technology, sensing, imaging, biophotonics and nanophotonics.

Optical antennas yield efficient coupling between the propagating field and the local electric field hence, show a strong analogy to their RF counterparts which collect radiated electromagnetic energy efficiently into a small volume on the receiver side, and provide more directive and efficient radiation of electromagnetic energy into a target volume on the transmitter side. Many well known RF antenna structures have been mapped to optics in this regard, yet, not so much attention has been paid to their design methods. The aim of this work is to implement the cavity model, an analytical and highly intuitive design and analysis method, for optical patch antennas.

Cavity model treats the RF patch antenna as a dielectric loaded cavity with electric conductors above and below and magnetic walls along the perimeter of the patch. The radiated field from a patch antenna is produced by the surface electric currents on the conducting patch. Equivalence principle shows that fields produced below the conducting patch, which closely resemble the resonant fields in the cavity, are equivalent to electric currents on the patch. Therefore, cavity model provides an analytical approach for patch antenna design and analysis. Optical patch antennas can also be analyzed via cavity model considering the differences due to lossy metal behavior in optics provided that similar surface currents are excited as of their RF counterparts’. Cavity model predicted antenna modes and corresponding radiation patterns are observed for optical patch antennas. Moreover, tools on circular polarization and frequency tuning are recorded for optical patches. This work indicates that cavity model, an analytical RF antenna design tool, can be mapped to optics as a complete package.

9163-80, Session 18

Plasmon-induced hot carriers in metallic nanoparticles

Alejandro Manjavacas, Jun Liu, Vikram V. Kulkarni, Peter Nordlander, Rice Univ. (United States)

Plasmon-induced hot carriers are attracting an increasing research interest due to its enormous potential applications to catalysis, photodetection and solar energy harvesting [1]. These excitations provide a very efficient mechanism for direct conversion of light energy into electronic energy that can be used to induce energetically unfavorable chemical reactions or to produce electrical currents. However, despite the enormous experimental effort, a complete theoretical understanding of the physical mechanisms behind the generation of plasmon-induced hot carriers is still missing [2].

In this work [3] we analyze the plasmon-induced hot carrier generation in metallic nanoparticles and nanoshells using a simple theoretical model in which the electrons are described as free particles in a finite spherical potential well, and the plasmon-induced dynamics is obtained through Fermi’s “golden rule”. Using the developed model we confirm that the number hot carriers generated follows the plasmonic spectral profile. Interestingly, we find that both the efficiency of the hot carrier generation and the energy of the hot carriers depend crucially on the size of the nanoparticle and on the electron lifetime. Furthermore, we analyze the importance of many-body effects by replacing the free electron wavefunctions with those obtained using density functional theory, finding an excellent agreement between both approaches, which supports the accuracy of our free electron model.

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9163-81, Session 18

Optical properties gold-silver alloy nanoparticles and their biomedical applications

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Gold silver alloy nanoparticles (NPs) are promising for chromatic labeling of biological material because of their composition-dependent plasmon resonance. For example, alloy NPs with various compositions can be used to target specific cells. Hyperspectral imaging of these cells can be used to spatially localize NPs on cells and extract the scattering spectrum of each NPs to identify their composition. Furthermore, because of the field enhancement at their surface, such NPs are also good candidates as SERS probes for cell labelling. In this case, NPs can be coated with a Raman reporter and functionalized to target specific cell receptors. Both chromatic and SERS labelling can be combined to provide highly-multiplexed detection of cells. It is important to understand and predict beforehand the optical properties of such alloy NPs in order to optimize them for SERS and chromatic labelling. We present an analytic model for the dielectric function of gold silver alloys. This model is based on the Drude model for the intraband contribution and on the analysis of the band structures of gold and silver for the interband contribution to the dielectric function. We use this model with Mie theory to predict the optical properties of alloy NPs. We namely study the influence of NPs size and composition on their extinction and scattering spectra as well as the electric field distribution around the nanostructures. These theoretical results are compared with the experimental scattering and Raman properties of alloy nanoparticles produced by femtosecond laser ablation.

9163-83, Session 18

Self-assembled nano-antennas by placing metallic nanoparticles on DNA-origami for enhancing the fluorescence intensity and photostability

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In this contribution, we introduce self-assembled DNA origami structures [1] as a platform where metallic nanoparticles as well as single organic fluorophores can be placed with nanometer precision. These hybrid structures were used to study the distance dependence quenching of fluorophores by gold nanoparticles [2] and to determine the fluorescence intensity angular dependence close to metallic nanoparticles [3]. Additionally, these structures were employed to built nano-antennas based on 100 nm gold dimers to focus light at the nano-scale leading to a fluorescence enhancement of more than two orders of magnitude [4] ready for single molecule measurements at concentrations as high as 500 nM [5]. Furthermore, we will report on the reduced photobleaching of organic dyes in the vicinity of gold nanoparticles with an increment of the number of total emitted photons. Finally we will introduce a method for experimentally determining the three relevant photophyscial rates (excitation, radiative and non radiative) that fully characterize the interaction between metallic structures and organic dyes based on the blinking kinetics.

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Sunday - Thursday 17–21 August 2014
Part of Proceedings of SPIE Vol. 9164 Optical Trapping and Optical Micromanipulation XI

9164-1, Session 1

Optical tweezing in a slow light medium

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Following by the Abraham-Minkowski controversy, which deals with correct expression of light linear momentum inside a medium, theoretical arguments suggest that the magnitude of the force exerted by a light beam on a dielectric object may depend on the group index of the object and on the group index of the surrounded medium. This, indeed, suggests a significant control on the optical forces, since the group index of a medium can vary over a significant range. In this work, we describe the status of our experimental effort aimed at determining the dependence of optical forces on group and refractive indices by means of optical tweezing. In particular, we study the case of dielectric particles embedded in an atomic gas and examine the optical forces acting on the particles when the light beam's frequency is close to the atomic resonance.

9164-2, Session 1

Cavity cooling a trapped nanosphere

Peter F. Barker, Piergiacomo Z. G. Fonseca, James Millen, Tania S. Monteiro, Univ. College London (United Kingdom)

We demonstrate the cooling of the center-of-mass motion of a dielectric nanoscale particle trapped in a Paul trap and in the optical field of a Fabry-Perot cavity in a vacuum [1,2]. This goal has recently been achieved for optically levitated nanoparticles at low vacuum[3], and for free nanoparticles passing through a cavity in high vacuum [4]. In our experiment, particles are confined within a Paul trap at the center of the cavity, allowing us to keep spheres trapped in high vacuum. The fundamental optical mode of the cavity is kept on resonance with a low-power laser beam by using the Pound-Drever-Hall technique, while a second higher power beam is red detuned from the cavity resonance to achieve cooling by dynamical back action. By analyzing the time dependence of the light scattered from the trapped particle in the cavity field, and by the the light transmitted through the cavity, we observe cooling of the motion of the particle using a modest cavity finesse of 14000. In this talk we will describe these experiments as well as newer experiments with a higher finesse cavity in the 10^5 range where we aim to achieve sideband cooling to the ground state.

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9164-3, Session 1

Doppler cooling microspheres

Peter F. Barker, Li Ying, Univ. College London (United Kingdom)

We describe experiments that are working towards cooling the center-of-mass motion of levitated silica microspheres via the velocity dependent scattering force from excitation of whispering gallery mode (WGM) resonances [1]. The technique is comparable to Doppler cooling as the motion is damped using light red detuned from the WGM resonance. This differs from conventional microparticle cavity cooling [2,3] as the microsphere acts as it's own high-Q (up to 109) cavity. Initial experiments have excited WGM resonances in a silica microsphere cantilever achieved by evanescent field coupling from a tapered optical fiber. We frequency lock the excitation laser to the WGM using the Pound-Drever-Hall locking scheme and damp the center-of-mass motion of the microsphere cantilever system. Further experiments will move to coolng free spheres that are optically trapped within an optical tweezer coupled to the evanescent light field, but uncoupled to the environment.

9164-4, Session 1

Parametric stabilization and cooling of microparticles in a quadrupole ion trap

Pavel Nagornykh, Bruce E. Kane, Univ. of Maryland, College Park (United States)

Discovery of graphene, 2D material with unique properties, led to intense search for a way to fully unlock its potential. It was found early that graphene strongly interacts with the substrate it is placed on, following the substrate topographically and is affected by its charge distribution. One of the ways to avoid this kind of interaction and access intrinsic physics of graphene is by levitating it so that only trapping fields are having any significant effect on the graphene. In our system we achieve the levitation by trapping charged flakes in home-built quadrupole trap in the UHV chamber. Particles are stabilized and cooled down after being trapped and transferred into the UHV chamber. In this talk we discuss the process used for particles' cooling and calibration of temperature, charge and mass of those particles by tracking amplitude and frequency of their motion. Current progress on controlling charge of graphene flakes in situ by using an electron gun is also discussed.

9164-5, Session 1

Dynamics of optically trapped microparticles in vacuum

Yoshihiko Arita, Michael Mazilu, Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

Quantum state preparation of mesoscopic objects is a powerful playground for the elucidation of many physical principles. These quantum regimes can only be achieved through laser cooling and by minimizing the state decoherence. An optically trapped nano- or micro-particle in vacuum is an ideal system for investigating quantum effects as the particle is well isolated from the thermal environment. Recently, we have demonstrated an optically trapped microgyroscope in vacuum, which leads to the positional stabilization in effect cooling the particle to 40K in all three translational directions without any feedback laser. This presents a novel and unique form of optomechanical system including the rotational degrees of freedom and is a major step towards measuring rotational quantum frictional forces in vacuum. We have extended the current system for multiparticle studies, which are essential for a number of key studies such as optical binding, multiparticle entanglement and quantum friction. We show the dynamics of multiple particles trapped and rotating in vacuum at different surface-to-surface distance (two to ten microns) between the particles. Further, we demonstrate for the first time microparticles trapped in more exotic optical landscapes, namely a Laguerre-Gaussian mode, wherein this case, particles orbit around the annular beam profile as well as spinning about their own axis when using a circularly polarized light field.

9164-6, Session 1

On-chip optical trapping for atomic applications

Maximillian A. Perez, Evan Salim, Dan Farkas, Janet Duggan, ColdQuanta, Inc. (United States); Megan Ivory, ColdQuanta Inc (United States); Dana Z. Anderson, ColdQuanta, Inc. (United States)

To simplify applications that rely on optical trapping of cold and ultracold atoms, ColdQuanta is developing techniques to incorporate miniature optical components onto in-vacuum atom chips. The result is a hybrid atom chip that combines an in-vacuum micro-optical bench for optical control with an atom chip for magnetic control. Placing optical components on a chip inside of the vacuum system produces a compact system that can be targeted to specific experiments, in this case the generation of optical lattices. Applications that can benefit from this technology include timekeeping, inertial sensing, gravimetry, quantum information, and emulation of quantum many-body systems.

ColdQuanta's GlasSi atom chip technology incorporates glass windows in the plane of a silicon atom chip. In conjunction with the in-vacuum micro-optical bench, optical lattices can be generated within a few hundred microns of an atom chip window through which single atoms can be imaged with sub-micron spatial resolution. The result is a quantum gas microscope that allows optical lattices to be studied at the level of single lattice sites.

Similar to what ColdQuanta has achieved with magneto-optical traps (MOTs) in its miniMOT system and with Bose-Einstein condensates (BECs) in its RuBECi® system, ColdQuanta seeks to apply the on-chip optical bench technology to studies of optical lattices in a commercially available, turnkey system. These techniques are currently being considered for lattice experiments in NASA's Cold Atom Laboratory (CAL) slated for flight on the International Space Station.

9164-7, Session 2

Quantum mechanics compatible Maxwell's stress tensor

Michael Mazilu, Univ. of St. Andrews (United Kingdom)

There are many ways to calculate the optical forces acting on scattering particles such as Maxwell's stress tensor, Lorentz forces, gradient and scattering forces, Lorenz-Mie formalism, T-matrix, etc…. All these approaches use the electromagnetic field and define the amount of linear momentum transferred to the scattering particles. By definition, the resulting momentum transferred is proportional to the intensity of the incident fields, however, the single photon momentum (hbar k) does not naturally appear in these classical expressions. In this paper, we discuss an alternative Maxwell's stress tensor based formalism that renders the classical electromagnetic field momentum compatible to the quantum mechanical one (hbar k). This same approach can be used for angular momentum and energy.

9164-8, Session 2

Calculating the optical gradient and scattering force and the creation of conservative optical force field

Jack Ng, Junjie Du, Isaac Yuen, Hong Kong Baptist Univ. (Hong Kong, China); Zhifang Lin, Fudan Univ. (China); Che Ting Chan, Hong Kong Univ. of Science and Technology (Hong Kong, China)

It is customary and useful to separate the optical force into two physically and mathematically distinct parts. The first is the conservative curl-less gradient force, which is responsible for optical trapping, producing optical potential landscape etc. The scattering force is responsible for Brownian motor, optical rotation, particle transportation etc.

Despite the importance of the concepts of gradient and scattering force, they have been calculated only for particle small or large compared to a wavelength. Nevertheless, these size regimes are not readily accessible in experiments, because small particle suffers from Brownian fluctuation while large particle suffers from strong gravity. The gradient and scattering force for the intermediate, experimentally accessible sizes have never been calculated before.

Here we report an analytical and a numerical approach to calculate the gradient and scattering force in the Mie regime. The analytical formulation provides insight and the independent numerical approach allows efficient calculation. The gradient and scattering force for various types of beams, including the widely employ fundamental Gaussian beam, will be presented.

Owing to the scattering force, a collection of particles illuminated by light do not come to equilibrium, instead it reaches a steady state. In many situations, a conservative force is preferable and it will be beneficial to eliminate the scattering force. We will present a recipe that allows us to eliminate the scattering force for spherical particles.

9164-9, Session 2

Momentum measurements with holographic optical tweezers for exploring force detection capabilities on irregular samples

Frederic Català , Univ. de Barcelona (Spain); Ferran Marsà Samper, Arnau Farré Flaquer, Mario Montes-Usategui, Impetux Optics, S.L. (Spain) and Univ. de Barcelona (Spain); Estela Martin-Badosa, Univ. de Barcelona (Spain)

Different methods allow measuring forces with optical tweezers. An attractive option relies on the detection of the momentum change of the trapping beam. This barely used alternative resorts to general principles and therefore provides a shorter route to the force, with clear advantages compared to other methods. As the magnitude is not derived from the sample displacement, no in situ calibration is required to obtain the force, and measurements are not restricted to specific conditions (spherical particle, Gaussian beam, homogeneous medium, etc.). Nevertheless, its combination with optical tweezers was not shown until recently, so its use has been restricted to the more complex counter-propagating beam geometry. With the use of gradient traps one gains more flexibility to, for example, combine force measurements with other technologies, such as spatial light modulators or acousto-optic deflectors that generate multiple traps. We show here how the measurement of the light momentum can be specifically used with holographic optical tweezers to leverage the potential of this force detection method. In particular, we show that forces can be measured with irregular particles and beams by simultaneously applying a force in the same direction by means of a constant flow to different holographically-trapped particles. This is, an important advantage compared to the traditional calibration approach.

9164-10, Session 2

Electromagnetic force and torque in Lorentz and Einstein-Laub formulations

Masud Mansuripur, College of Optical Sciences, The Univ. of Arizona (United States)

The classical theory of electrodynamics is built upon Maxwell's equations and the concepts of electromagnetic field, force, energy, and momentum, which are intimately tied together by Poynting's theorem and the Lorentz force law. Whereas Maxwell's macroscopic equations relate the electric and magnetic fields to their material sources (i.e., charge, current, polarization and magnetization), Poynting's theorem governs the flow of electromagnetic energy and its exchange between fields and material media, while the Lorentz law regulates the back-and-forth transfer of momentum between the media and the fields. As it turns out, an alternative force law, first proposed in 1908 by Einstein and Laub, exists that is consistent with Maxwell's macroscopic equations and complies with the conservation laws as well as with the requirements of special relativity. While the Lorentz law requires the introduction of hidden energy and hidden momentum in situations where an electric field acts on a magnetic material, the Einstein-Laub formulation of electromagnetic force and torque does not invoke hidden entities under such circumstances. Moreover, the total force and the total torque exerted by electromagnetic fields on any given object turn out to be independent of whether force and torque densities are evaluated using the Lorentz law or in accordance with the Einstein-Laub formulas. Hidden entities aside, the two formulations differ only in their predicted force and torque distributions throughout material media. Such differences in distribution are occasionally measurable, and could serve as a guide in deciding which formulation, if either, corresponds to physical reality.

9164-11, Session 3

Optical vault: a reconfigurable bottle beam based on conical refraction of light

Wieslaw Z. Krolikowski, The Australian National Univ. (Australia) and Texas A&M Univ. at Qatar (Qatar); Alejandro Turpin, Univ. Autònoma de Barcelona (Spain); Vladlen G. Shvedov, Cyril Hnatovsky, The Australian National Univ. (Australia); Yurii V. Loika, Univ. of Dundee (United Kingdom); Jordi Mompart, Univ. Autònoma de Barcelona (Spain)

We study trapping of absorbing particles by using an optical bottle formed via conical diffraction of circularly polarized light beam in biaxial KTP crystal. When the circularly polarized beam propagates along one of the optical axes of biaxial crystal the beam outside the crystal forms an optical bottle, i.e. it acquires a form of dark circularly symmetric area surrounded by high light intensity. When the incident light is of linear polarization the emerging pattern loses its circular symmetry. Instead of the rings, the transverse light intensity distribution now takes the form of crescents, which are produced within a certain interval along propagation direction. In 3-D, this implies the formation of a gap in the side wall of the otherwise perfect optical bottle. In our experiments we employed 11.3 mm long KTP crystal. illuminated by 100mW laser beam at 532nm wavelength to create the bottle which was subsequently used to trap glass shells covered with a thin layer of carbon (~200 nm) in order to make them light-absorbing. To prevent accidental air flows from affecting the trapping process, the optical bottle was formed inside a transparent cylindrical glass cell placed immediately behind the biaxial crystal. We found that while a particle could be trapped using either a fully closed (i.e., circular input polarization) or opened (i.e., linear input polarization) bottle, the loading much faster in the latter case. The trapping was generally very robust, with the particles stably resting at the lower light wall due to gravity. The ability to open or close the bottle at will by varying the input beam polarization gives a unique opportunity not only to easily trap micro-objects but also to release them.

9164-12, Session 3

Shaping self imaging optical bottles with modified quasi-Bessel beams

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Coherent generated of self-imaging bottle beams, typically formed by interfering two coherent Quasi-Bessel beams, possess a periodic array of intensity maxima and minima along their axial direction. In practice, the overall quality of the self-repeating intensity patterns possesses large intensity variations that have yet to be unresolved. In this paper, we increase consistency of intensity of self-imaging bottle beams through a spatial frequency optimization routine. By doing so, we increased the effective length of self-imaging bottle beams by 74%. Further, we show that this approach is applicable to higher-order self-imaging beams which display complex intensity structures. The enhancement in these modified self-imaging beams could play a significant role in optical trapping, imaging and lithography.

9164-13, Session 3

Focusing and imaging with increased numerical apertures through multimode fibers with micro-fabricated optics

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The use of individual multimode optical fibers in endoscopy applications has the potential to provide highly miniaturized and noninvasive probes for microscopy and optical micromanipulation. A few different strategies have been proposed recently, but they all suffer from intrinsically low resolution related to the low numerical aperture of multimode fibers. Here, we show that two-photon polymerization allows for direct fabrication of micro-optics components on the fiber end, resulting in an increase of the numerical aperture to a value that is close to 1. Coupling light into the fiber through a spatial light modulator, we were able to optically scan a submicrometer spot (300 nm FWHM) over an extended region, facing the opposite fiber end. Fluorescence imaging with improved resolution is also demonstrated.

9164-15, Session 3

Engineering particle trajectories in microfluidic flows using speckle light fields

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Current optical trapping techniques rely on carefully engineered setups to manipulate nanoscopic and microscopic objects at the focus of a laser beam. Since the quality of the trapping is strongly dependent on the focus quality, these systems have to be very carefully aligned and optimized, thus limiting their practical applicability in complex environments. One major challenge for current optical manipulation techniques is the light scattering occurring in optically complex media, such as biological tissues, turbid liquids and rough surfaces, which give rise to apparently random light fields known as speckles. Here, we present a novel experimental technique for optical manipulation based on speckles. We experimentally show how to take advantage of the statistical properties of speckle patterns in order to perform basic optical manipulation tasks such as trapping, guiding and sorting. In particular, we demonstrate sieving and sorting of Brownian particles of different size (2 and 5 μm) and refractive index ($n = 1.42$ and $n = 1.68$) in a microfluidic chamber. The speckle pattern to perform such tasks, is generated by mode mixing in a multimode optical fiber so that an incident laser power as little as a few tens of microWatt per square micrometer (maximum power = 30 μW/μm2) is needed. Moreover, apart from the excitation laser, all the components needed to generate the speckle pattern can be integrated in the walls of the microfluidic chamber. The simplicity of this technique will foster its application in biological and biomedical applications where automated and turn-key techniques are especially appreciated.

9164-92, Session 3

Spontaneous revolution of micro-swimmers in a spherically aberrated optical trap

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Artificial micro-swimmers are fast emerging as models to mimic and thereby understand the movement patterns of microorganisms and biological cells which self-propel themselves by generating fields or gradients that cause fluid flow around their surface by phoretic surface effects, such as thermophoresis [1] or electrophoresis [2]. In this paper, we demonstrate that radiation pressure can lead to spontaneous revolution of a micron-sized asymmetric particle inside an annular potential formed due to geometrical aberrations of a Gaussian beam focused into a stratified medium using a high numerical aperture microscopic objective [3]. The rate of revolution can be controlled from a few Hz to tens of Hz by changing the intensity of the trapping light which can be achieved either by modifying the laser power or the annular trap diameter. Theoretical simulations performed using Finite-difference time-domain method in Lumerical verify the experimental observations. The electric field distribution confirms that the particle revolution is the effect of asymmetrical scattering by the particle in the annular potential that gives rise to a tangential force. A proper Maxwell stress-tensor analysis of the problem demonstrates this uniform tangential force acting on the particle inside the ring. The model also shows that particles could be custom designed in order to spontaneously revolve in such annular trapping potentials. Thus, such systems could be used in place of LG beams to apply torque on DNA strands in order to study protein-DNA interaction [4], or to study the hydrodynamic synchronization [5] among multiple rotating objects.Reference:

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9164-16, Session 4

Observation of the rotational Doppler effect from an optically trapped micro-particle

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The linear Doppler shift forms the basis of various sensor types for the measurement of linear velocity, ranging from speeding cars to fluid flow. Recently, it has been shown that similar effects can be observed for rotating objects even when the linear Doppler shift is zero. If measurement of the light scattered from a rotating object is restricted to a mode corresponding to a defined state of Orbital Angular Momentum (OAM), then a frequency shift is observed given as the product of the rotation rate of the object, and the OAM of the scattered photon. Illuminating the spinning surface with two beams of opposite handedness OAM, hence giving rise to opposite frequency shifts, results in interference and an intensity modulation from which the rotation speed can be deduced.

Here, we measure the rotational Doppler shift from micron sized calcite particles spinning within an optical tweezers in water at 10s of Hz. In this case the signal is complicated by the geometry of the particle, and its Brownian motion. We describe how the rotational Doppler shift signal can still be used to measure the particle's rotation rate.

9164-17, Session 4

Optical trapping with a perfect vortex beam

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Vortex beams with different topological charge usually have different profiles and radii of peak intensity. This introduces a degree of complexity the fair study of the nature of optical OAM (orbital angular momentum). To avoid this, we introduced a new approach by creating a perfect vortex beam using an annular illuminating beam with a fixed intensity profile on an SLM that imposes a chosen topological charge. The radial intensity profile of such an experimentally created perfect vortex beam is independent to any given integer value of its topological charge. The well-defined OAM density in such a perfect vortex beam is probed by trapping microscope particles. The rotation rate of a trapped necklace of particles is measured for both integer and non-integer topological charge. Experimental results agree with the theoretical prediction. With the flexibility of our approach, local OAM density can be corrected in situ to overcome the problem of trapping the particle in the intensity hotspots. The correction of local OAM density in the perfect vortex beam therefore enables a single trapped particle to move along the vortex ring at a constant angular velocity that is independent of the azimuthal position. With such a vortex field in hand, we further investigate the quantisation of OAM. Due to its particular nature, the perfect vortex beam may be applied to other studies in optical trapping of particles, atoms or quantum gases.

9164-18, Session 4

Behavior of oblate spheroidal microparticles in a tightly focused optical vortex beam

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Behaviour of dielectric microparticles optically confined in a focused optical vortex beam will be investigated. Comparison of our own precise experimental measurements with theoretical model will be presented and discussed for various topological charges and beam polarizations.

9164-19, Session 4

Interesting manifestations of spin orbit interaction and spin Hall shift of light in an optical trap

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The spin orbit interaction (SOI) of light leading to the evolution of trajectory dependent geometric phase and associated spin Hall

shift (SHS) in circularly polarized light has led to several fascinating manifestations in scattering, tight focusing, and imaging processes. However, most of these observations are at the sub-wavelength level, with somewhat limited applications of a general nature. We investigate the SOI in an optical trap for a linearly polarized trapping beam where the both the trajectory dependent geometric phase as well as the SHS are magnified significantly due to a stratified medium. The stratified medium is created using an index mismatched cover slip that modifies the radial intensity distribution near the focal plane of the trap due to diffraction effects. The modified intensity distribution causes trapping of polystyrene beads in ring-like patterns, while the tight focusing in the stratified medium also leads to a large spin redirectional geometric phase that creates intensity side lobes in the azimuthal direction near the focal plane. Single trapped asymmetric particles can be trapped in the side lobes and translated along the ring by changing the polarization angle of the input beam. A 3D analysis of polarization reveals the generation of polarization vortices as well as spatially separated regions of opposite circular polarizations near the focal plane leading to controlled rotation of trapped particles, again by a linearly polarized input beam. The study can have several interesting consequences in the manipulation of mesoscopic particles in an optical trap.

9164-20, Session 4

Helicity-dependent optomechanics of chiral microparticles *(Invited Paper)*

Etienne Brasselet, Georgiy V. Tkachenko, Univ. Bordeaux 1 (France)

To exploit the angular momentum degree of freedom of the light to control the mechanical effects that results from its linear momentum is an intriguing challenge that may open several new routes towards enhanced optical trapping, manipulation and sorting of microscopic entities. This issue can be addressed by exploiting the interplay between the chirality of matter and the chirality of optical fields. Here we will report on our recent progresses on helicity-dependent optomechanics of chiral microparticles.

9164-21, Session 5

Measurement of interparticle force between nematic colloids by optical tweezers

Yasuyuki Kimura, Kuniyoshi Izaki, Kyushu Univ. (Japan)

When the micrometer-sized colloidal particles are dispersed in nematic liquid crystal which have orientational order, the particles (nematic colloids) themselves become topological defects and spontaneously induce another defects to relax the deformation around the particles. They also interact with each other via characteristic anisotropic interaction to reduce the orientaitonal elastic energy of liquid crystal. There are various kinds of nematic colloids with different detects and their interaction is different each other. In this study, we directly measured the interparticle force between the same and the different types of nematic colloids by various methods utilizing optical tweezers. The measured interaction can be both attractive and repulsive depending on the relative arrangement of the particles. The obtained force is quantitatively well described by the elastic theory of liquid crystal.

We also construct various exotic microstructures those cannot be realized in isotropic liquids by optical tweezers. For example, although the particles with attractive interaction will take compact structures in isotropic liquid, the anisotropic attractive and repulsive interaction in nematic colloids enables us to construct stable open structures such as dendric or snowflake-like structures.

9164-22, Session 5

Optical tweezers rotational microrheology: achieving viscoelastic measurements in confined geometries

Lachlan Gibson, Daryl C. Preece, Timo A. Nieminen, Halina H. Rubinsztein-Dunlop, The Univ. of Queensland (Australia)

Many biological fluids, including the cytoplasm inside cells, synovial fluid between bone joints and tear film, manifest both viscous and elastic properties. Measuring the viscoelasticity of these fluids is difficult because they can be highly inhomogeneous or only available in ultra-small volumes. Conventional rheological techniques are precluded from measuring the properties of these fluids because they require large samples (mL). As a result, it has been necessary to develop an optical tweezers microrheometer which functions in ultra-low volumes (pL) or inside confined spaces. Our novel optical tweezers microrhemeter achieves superb temporal (~mHz-kHz) and spatial resolution by observing both passive and active rotational dynamics of a single optically trapped particle. The probe particles are birefringent vaterite microspheres allowing the particle's azimuthal angle to be accurately controlled and monitored with a high sampling rate. High frequency viscoelastic data is measured by observing rotational Brownian motion while lower frequencies can be evaluated by actively rotating the particle between two coaxial angularly offset traps. Analysis of the active measurements in ethanol confirms the existence of a non-linear angle dependent optical torque exerted by the trap. Microrheological measurements in water, ethanol and dilutions of Celluvisc eye drops agree with macrorheological data. These results demonstrate the accuracy and high temporal resolution of this method. Further measurements inside artificial liposome spheres could confirm the expected spatial resolution which would motivate investigations into the precise properties of highly inhomogeneous fluids or to take rheological measurements in confined geometries such as a cell.

9164-23, Session 5

Anti-reflection coated particles for biophysical measurements

Derek Craig, Igor Andreyev, Yoshihiko Arita, Michael Mazilu, David C. Hamilton, Peter Pogorzelec, Kishan Dholakia, Univ. of St. Andrews (United Kingdom)

Improvements in optical tweezing have largely focused on modifications of instrumentation and the shaping of the trapping beam. Recent advances in this area have exploited the more pertinent component of optical tweezing, the physical and material properties of the trapped particle. The production of anti-reflection coated, high-refractive index core-shell microparticles (AR particles) has broadened the capacity for optical trapping investigations with optical forces greater than a nanonewton having been reported. Here, we demonstrate the reproducible synthesis of such particles with comparable trap stiffnesses to those previously reported.

Building on this concept we have performed the first set of biophysical measurements using these particles, including the exploration of cell microrheology, to manipulate the stretching of red blood cells (RBC) and their use in flow viscosity measurements. The advantages of these particles opens up new directions for optical trapping studies

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9164-24, Session 5

Quantifying change in stiffness heterogeneity in 3D around cells embedded in natural ECMs over time

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Cells within their microenvironment engage in a ‘push-pull’ relationship with their surrounding extracellular matrix (ECM). The ECM mesh is readily deformed by cell-generated forces and ECM stiffness increases with local mesh deformation. Thus, we cannot infer forces acting on or generated by cells if we measure local deformation alone. The changing stiffness must be measured as well. To investigate roles for forces and ECM stiffness we culture cells within 3D ECM hydrogels containing microbeads. We implement automated optical tweezers active microrheology (aAMR) to map ECM stiffness surrounding cells. Hundreds of beads are probed in one hour to map the mechanical landscape and to seek correlations between local stiffness and cell properties such as contractility, signaling and differentiation. To estimate forces acting on each bead we first map stiffness around the same cell over time, carefully probing the same beads at each time point. Forces are estimated as the product of bead displacement and stiffness.

We cultured primary human aortic smooth muscle cells (AoSMCs) within collagen hydrogels and observed local stiffness ranging by an order of magnitude. Cells were treated with inhibitors of contractility after which microbeads displaced towards cells while local ECMs softened significantly. Time-lapse aAMR shows ECM stiffening at the leading front of migrating cells and a loose correlation between bead displacement and force, reinforcing our assertion that traction forces cannot be measured without consideration of the heterogeneous scaffold of the local ECM.

9164-26, Session 5

Temporal response of biological cells to high-frequency optical jumping and vibrating tweezers

Lingyao Yu, Yunlong Sheng, Univ. Laval (Canada)

Vibrating and jumping laser beams are recently used for tugging, wiggling and stretching biological cells and macromolecules with Pico-Newton forces. A laser beam can jump to several locations in the cell to implement multiple traps in time-sharing regime. Laser beam trapped the proximity of the cell and vibrated in position for an active rheology assay. Dynamic viscoelasticity of the cell was measured in high-throughput flow cytometer, where the cell flows into a channel formed by one-dimensionally focused linear diode laser bars with vibrating intensity. In many cases however the analysis was only a too simplified. The time-sharing optical tweezers was based on an intuitive concept that a viscoelastic object does not “sense” blinking of the optical beam, so that a jumping beam is equivalent to a static multi-trap. In many cases the biological object was modeled as a 1D circuit of springs and dashpots, or as material of inelastic 1D power law without considering the real 3D shape and internal structure of the cell. We used the finite element method to model full 3D structure, viscoelastic continuum materials of the cell and its temporal response to high-frequency jumping and vibrating of the external load. New phenomena were studied and might be further investigated with more accurate experiments, such as the jumping of local stress and local strain independently on the material recovery time and the jumping frequency; the energy dissipation in the hysteresis cycles etc. Moreover, the cytoplasm fluid field and its interaction with the cell membrane are investigated

9164-27, Session 6

Local probing and stimulation of neuronal cells by optical manipulation *(Invited Paper)*

Danut-Adrian Cojoc, CNR-IOM (Italy)

During development and in the adult brain, neurons continuously explore the environment searching for guidance cues, leading to the appropriate connections. Elucidating these mechanisms represents a gold goal in neurobiology. Here, I discuss our recent achievements developing new approaches to locally probe the growth cones (GC) and stimulate neuronal compartments with high spatial and temporal resolution.

Optical tweezers force spectroscopy applied in conjunction with metabolic inhibitors reveal new properties of the filopodia and lamellipodia dynamics of GC [1].

On the other hand, using optically manipulated (OM) microvectors as functionalized beads or filled liposomes, we demonstrate focal stimulation of neurons by small number of signaling molecules. For example, beads coated with Brain Derived Neurotrophic Factor and OM to specific sites on the dendrites, are shown to trigger TrkB receptor pathway [2]. Since beads can be easily functionalized with any type of protein, the technique can be generalized for many other schemes of stimulation. However, since the molecules cannot leave the bead surface this approach cannot be applied for experiments requiring freely diffusing molecules. Therefore we have considered another type of vector: filled liposomes, where molecules are released by liposome membrane photolysis. This approach allows to scale down to very small numbers of molecules as we demonstrate for guidance molecules Netrin-1 and Semaphorin3A [3,4,].

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9164-28, Session 6

MicroTsunamis: a method for high-throughput screening of cellular mechanotransduction using laser microbeam generated cavitation bubbles

Jonathan Compton, Justin Luo, Huan Ma, Vasan Venugopalan, Elliot L. Botvinick, Univ. of California, Irvine (United States)

We introduce an all optical platform for rapid, high-throughput screening of exogenous molecules affecting cellular mechanotransduction without reliance on flow chambers or microfluidics. Our method initiates mechanotransduction in adherent cells using single laser-microbeam generated micro-cavitation bubbles (µCBs). These µCBs expose adherent cells to a microTsunami: a transient microscale burst of hydrodynamic shear stress that stimulates cells over areas approaching 1mm2. We demonstrate microTsunami-initiated mechanosignaling in primary human endothelial cells. This observed signaling is consistent with G-protein-coupled receptor stimulation, a hallmark of mechanotransduction, resulting in Ca2+ release by the endoplasmic reticulum. Moreover, we show dose-dependent modulation of Ca2+ signaling through exogenous administration of a known inhibitor to this pathway. We utilize this capability to screen the effects of a set of small molecules on cellular mechanotransduction in 96-well plates using standard imaging cytometry.

9164-29, Session 6

Force measurements with optical tweezers inside living cells

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Andrews (United Kingdom); Arnau Farré Flaquer, Impetux Optics, S.L. (Spain) and Univ. de Barcelona (Spain); Jordi Sancho-Parramon, Institut Ruder Boškovic (Croatia); Estela Martín-Badosa, Univ. de Barcelona (Spain); Mario Montes-Usategui, Univ. de Barcelona (Spain) and Impetux Optics S.L. (Spain)

The study of intracellular transport with optical traps has made a remarkable step ahead in recent years translating the debate about the mechanochemical properties of motor proteins to their natural environment: the cell. Different works have shown the possibility to obtain reliable information of molecular motors inside cells at the single-molecule level. The opportunity to carry experiments in vivo opens the field to new questions which were not addressable until now. This change has been driven by the advent of new calibration methods for measuring forces in cells. Here, we present an alternative method for optical tweezers, based on the detection of the light momentum changes of the trapping beam. The force measurements follow this more general principle and are therefore less vulnerable to particular conditions of the experiment as no approximations relative to the interaction between the sample and the beam are required. The instrument is calibrated by measuring some parameters exclusively related to its optical design so that it is possible to obtain a conversion factor from volts to piconewtons that is independent of the physical properties of the sample and the beam. We compared this value with calibrations performed in vivo on different lipid droplets through the active-passive method proposed by Berg-Sørensen et al., and found a remarkable agreement between both. The results show that the measurement of forces on arbitrary-shaped biological objects inside cells without an in situ calibration is feasible. We found that our measurements were barely affected by the presence of other structures, such as neighbouring vesicles or the cell membrane. We finally used the instrument to measure the stall forces of kinesin and dynein inside A549 cells.

9164-30, Session 6

Measuring local viscosities near membranes of living cells with photonic force microscopy

Felix Jünger, Alexander Rohrbach, Albert-Ludwigs-Univ. Freiburg (Germany)

The diffusive motion of a particle in the vicinity of a boundary surface is relevant from a biological point of view, since the viscous drag γ changes significantly with the distance to the interface such as a cell membrane. In this study we use photonic force microscopy (PFM) to investigate how γ changes when an optically trapped 1µm polystyrene bead approaches the plasma membrane of different biological cells. The bead's temporal fluctuations are tracked interferometrically in three dimensions with nanometer precision and on a microsecond time scale. The autocorrelation of the bead's motion reveals the friction coefficient γ(d) as a function of bead-membrane distance d.

We investigated the hydrodynamic decay length γ(d) for different cell types (J774, HT29, MDCK) and a giant unilamellar vesicle (GUV). Consisting only of a lipid bilayer and lacking cytoskeleton and molecular motors, the GUVs serve as a model for biological cells with greatly reduced complexity. Interestingly, we find that all decay lengths γ(d) measured at biological membranes are significantly longer than those of a rigid glass coverslip, giving rise to the conclusion that the deformable shape of the membrane influences the hydrodynamic interaction. The precise knowledge of γ(d) enables us to determine another biologically relevant quantity, the mean first passage time (MFPT). All cell types investigated show significantly enlarged and furthermore anisotropic MFPTs for diffusion close to the membrane.

9164-31, Session 6

Structuring bacterial biofilms on the single-cell level using optical trapping

Vernita Gordon, Jaime Hutchison, Christopher Rodesney, Karishma Kaushik, Henry Le, Daniel Hurwitz, Yasuhiko Irie, The Univ. of Texas at Austin (United States)

In biofilm infections, changes in bacterial phenotype result from spatial structure and can impact the clinical tractability and outcome. Understanding the role of spatial structure requires methods to control the spatial structure of biofilms. We control the initial positions of bacteria at the begining of biofilm formation by using laser trapping to place single cells on the glass coverslip of a flow cell. The challenge was developing a protocol such that laser trapping does not impinge bacterial viability. We do so by working at minimal oxygen levels and by keeping the time a cell stays in the optical trap to less than three minutes. We demonstrate that trapping has not permanently-altered cell behavior by comparing the doubling times of trapped cells and their descendants to the doubling times of never- trapped cells, for P. aeruginosa and S. aureus, two important human pathogens that form biofilm infections.

Our technique can reveal effects of spatial structure in early biofilm formation that could not be studied using conventional techniques for biofilm culture. We show this for two cases: (1) In an appropriate culture environment, P. aeruginosa in small clusters grow 15% faster than non-clustered P. aeruginosa (p-value <0.0001). (2) A few P. aeruginosa cells increase the doubling time of S. aureus by 10% (p-value 0.06).

Because the laser trap we use is very basic and the other equipment required is inexpensive and standard, we believe that our technique will be a widely-usable tool for biological and physical collaborators at many types of institutions.

9164-32, Session 6

Tailored manipulation of rod-shaped bacteria and adhesive cellular clusters with tug-of-war optical tweezers

Anna S. Bezryadina, San Francisco State Univ. (United States); Daryl C. Preece, The Univ. of Queensland (Australia); Zhigang Chen, Joseph C. Chen, San Francisco State Univ. (United States)

In this work we demonstrate a new approach to achieve stable in-plane optical trapping and full control of rod-shaped bacteria. This approach is based on specially designed "tug-of-war" optical tweezers which better match bacteria morphology and thus require less trapping power. Such "tug-of-war" tweezers avoid the problem of flipping or self-aligning of rod-shaped objects inevitable in conventional dual trap tweezers. More importantly, these optical tweezers can be used simultaneously as an optical stretcher, applying a tunable lateral pulling force to a cell or a cell cluster with better stability and larger lateral forces. Both scattering and gradient forces work in pulling bacteria apart. In particular, we demonstrate that the pulling force is strong enough to break up strongly adhesive cellular clusters of bacteria in aqueous media. For example, S. meliloti cells nominally are about 2 ?m long in rod shape, but different chemicals and structures are generated during specific growth periods which allow the bacteria to adhere to each other and form long clusters of cells. With the "tug-of-war" tweezers, we can identify the strong and weak clustering of S. meliloti cells as a function of the growth media and/or different pH levels. Our approach may help to reveal new perspectives on bacterial cellular clustering and aggregation, and the "tug-of-war" optical tweezers may find a variety of applications in studying cellular viscoelasticity, cell motility, and intercellular interactions.

9164-33, Session 6

The Pocketscope: a spatial light modulator based epi-fluorescence microscope for optogenetics

Anna Linnenberger, Univ. of Colorado (United States); Rafael Yuste M.D., Darcy Peterka, Columbia Univ. (United States); Sean Quirin, Columbia University (United States)

Microscopy with spatial light modulators (SLMs) enables use of optical techniques to study neuronal circuit activity, allowing the ability to both monitor and manipulate the activity of neuronal ensembles, in vitro and in vivo. In this paper we present a portable (22 cm x 42.5 cm x 30 cm), SLM-based epi-fluorescence upright microscope ("Pocketscope"). The core of this technology takes advantage of algorithms and techniques developed for holographic optical tweezers. However, the tool is no longer used to manipulate the position of objects within a 3D volume. Instead the volume of focal points are used as an enabling tool to probe and manipulate neural circuits in the brain. Here we describe the implementation of the instrument, and demonstrate 3D calcium imaging of neurons in brain slices.

9164-34, Session 6

Optical heating of Gold Nanoparticles as a Tool for investigating Membrane Phase Behavior

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Cell membranes show great heterogeneity with laterally organized ordered and disordered nanoscale domains. The functional importance for cells to dynamically organize the membrane into domains of different order could be to transiently cluster signaling proteins in a nanoscale environment to facilitate chemical reaction between membrane proteins by proximity. The transient nature of so called ordered raft domains makes it difficult to study dynamic phase behavior of cell membranes. We have developed a new assay to create local phase changes in Giant Unilamellar lipid Vesicles (GUVs) by using an optically trapped gold nanoparticle to locally heat the lipid membrane and induce a phase transition. Membrane phase transitions can be rapidly turned on and off by controlling the laser power or the distance between the heated nanoparticle and the membrane. By using phase sensitive fluorophores we can clearly detect the size of the region that has undergone a phase transition. By using a self-quenched dye encapsulated within the GUV we are able to detect single permeation events, associated with the locally melting membrane, when the encapsulated dye de-quenches into the extravesicular solution. Importantly, our results reveal that a phase transition in a lipid bilayer is associated with transient and localized permeation having similar lifetimes as ion channel conductance measured in patch clamp experiments on cell membranes.

9164-35, Session 7

Quad stereomicroscopy

Rebecca F. Hay, Graham M. Gibson, Michael P. Lee, Miles J. Padgett, David B. Phillips, Univ. of Glasgow (United Kingdom)

Stereomicroscopy enables a sample to be imaged from directions directions simultaneously by using two illumination sources, which allows the tracking of microscopic objects in three dimensions.

In stereomicroscopy, each illumination direction produces an individual image, which would normally be combined into one single image that is viewed in the imaging plane. By placing a spatial light modulator (SLM) in the Fourier plane of the stereomicroscope, it is possible to separate these multiple images. By performing 2-dimensional image tracking analysis on each image, the 3-dimensional coordinates of an object can be recovered using parallax. This is powerful technique when combined with Holographic Optical Tweezers, as multiple trapped objects can be tracked in three dimensions without the need for calibration images.

We now plan to extend this to four different illumination directions, quad stereomicroscopy. This gives a direct measurement of the error in particle tracking. We use the SLM again to separate the four images. There is also a fifth on axis illuminator, for observing the undistorted 2D image, while the quad illumination is simultaneously used to obtain the 3D information.

We investigate how changing the angle between the illumination and sample affects 3D tracking in the system, and determine the optimum angle for stereomicroscopic tracking.

9164-36, Session 7

Enabling accurate photodiode detection of multiple optical traps by spatial filtering

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Dual and multiple beam optical tweezers allow for advanced trapping geometries beyond single traps, however, these increased manipulation capabilities typically come at the price of more challenging position and force detection. The accuracy of position and force measurements is often compromised by crosstalk between the detected signals, this crosstalk leading to a systematic error on the measured forces and distances. This is true both for dual-beams optical traps and multiple beam optical traps. In a dual-beam optical trapping facility, the two traps are often orthogonally polarized and cross-talk can be minimized by inserting polarization optics in front of the detector, however, this method is not perfect because of the de-polarization of the trapping beam introduced by the required high numerical aperture optics. Here we present an easy-to-implement simple method to efficiently eliminate cross-talk both in dual beam and multiple beam setups. The method is based on spatial filtering and is highly compatible with standard back-focal plane photodiode based detection of position and force. In a dual-beam setup, our spatial filtering method reduces cross-talk up to 500 percent better than polarization filtering alone. The methodology here proposed enables fast, easy, and convenient photodiode detection of forces and distances in multiple trapping platforms and significantly improves the accuracy of force-distance measurements, e.g., of single molecules, hence providing much more scientific value for the experimental efforts.

9164-37, Session 7

A force measurement instrument for optical tweezers based on the detection of light momentum changes

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In optical tweezers, forces are typically determined by virtue of the linear relation between force and sample displacement, which requires the calibration of the system to obtain the conversion factor between both magnitudes. Unfortunately, the calibration depends in a strong manner on the physical properties of the sample and needs hence to be determined prior to performing an experiment. An alternative solution is based on the detection of the momentum change of the trapping beam, a much less used approach because of the practical difficulties in its implementation. The force is a magnitude that cannot typically be obtained through a direct measurement but it is more often derived from an additional quantity, such as the position. Following the direct route, by contrast, has multiple advantages as force is determined from first principles and provides therefore a direct access to this information. For example, once the instrument is calibrated, forces are measured regardless of the nature of the sample, or without requiring an in situ calibration. Here, we present a force sensor instrument based on this method, which, although originally devised for counter-propagating beams, can be

adapted to operate with optical tweezers. The developed instrument incorporates technical solutions that overcome the practical difficulties when the momentum method is implemented. We specifically show the requirements that an instrument based upon this method must fulfill in order to operate with single-beam gradient traps, as well as the optical and electronic improvements needed to obtain a high-precision force calibration, which is constant and permanent.

9164-38, Session 7

Optical tweezers escape forces

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Optical tweezers can be used to measure forces within microscopic environments.To do this, the optical trap needs to be calibrated. Two quantities are of most interest: the spring constant, and the maximum force exerted by the trap. The latter is the force required to escape from the trap. One method to determine this is to use viscous drag to remove a particle from the trap, typically by moving the stage. The stage velocity required to remove the particle then gives the escape force. However, the escape force can vary by up to 30%, depending on the particle trajectory. This is seen in experiments in different laboratories, and further confirmed by simulation. This can have significant quantitative impact on measurements. We describe the variation of escape force and escape trajectory, using both experimental measurements and simulations, and discuss implications for experimental measurement of forces.

9164-39, Session 7

A new technique for high sensitive detection of rotational motion in optical tweezers by a differential measurement of backscattered intensity

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Asymmetric particles, such as biological cells, often experience torque under optical tweezers due to birefringence or unbalanced scattering forces, which makes precise determination of the torque crucial for calibration and control of the particles. The estimate of torque relies on the accurate measurement of rotational motion, which has been achieved by various techniques such as measuring the intensity fluctuations of the forward scattered light [1], or the polarization component orthogonal to the trapping light polarization in plasmonic nanoparticles [2] and vaterite crystals [3]. Here we present a simple yet high sensitive technique to measure rotation of such an asymmetric trapped particle where the scattered light is elongated in shape by detecting the light backscattered onto a quadrant photodiode, and subtracting the signals along the two diagonals of the quadrants. This automatically suppresses the common mode translational signal obtained by taking the difference signal of the adjacent quadrants, while amplifying the rotational signal. Using this technique, we obtain a S/N of 200 for angular displacement of a trapped micro-rod by 5 degrees, which implies a sensitivity of 50 mdeg with S/N of 2. We also detect the rotational Brownian motion of red blood cells which acquire a small form birefringence and asymmetric shape when placed in a hypotonic NaCl solution, leading to the rotational component that may be too weak to detect by polarization dependent detection techniques. The technique is thus independent of birefringence and polarization properties of the asymmetric particle and depends only on the scattering cross-section.

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9164-40, Session 7

Optical tweezers calibration with Bayesian inference *(Invited Paper)*

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We present a new method for calibrating an optical-tweezer setup that is based on Bayesian inference [Richly et al., Opt. Express 2013]. This method employs an algorithm previously used to analyze the confined trajectories of receptors within lipid rafts [Türkcan et al., Biophys. J. 2012]. The main advantages of this method are that it does not require input parameters and is insensitive to systematic errors like the drift of the setup. Additionally, it exploits a much larger amount of the information stored in the recorded bead trajectory than standard calibration approaches. The additional information can be used to detect deviations from the perfect harmonic potential or detect environmental influences on the bead. The algorithm infers the diffusion coefficient and the potential felt by a trapped bead, and only requires the bead trajectory as input. We demonstrate that this method outperforms the equipartition method and the power-spectrum method in input information required (bead radius and trajectory length) and in output accuracy. Furthermore, by inferring a higher order potential our method can reveal deviations from the assumed second-order potential. More generally, this method can also be used for magnetic-tweezer calibration.

9164-41, Session 8

STED nanoscopy combined with optical tweezers reveals protein dynamics on densely covered DNA

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Dense coverage of DNA by proteins is a ubiquitous feature of cellular processes such as DNA organization, replication and repair. We present a single-molecule approach capable of visualizing individual DNA-binding proteins on densely covered DNA and in the presence of high protein concentrations. Our approach combines optical tweezers with multicolor confocal and stimulated emission depletion (STED) fluorescence microscopy. Proteins on DNA are visualized at a resolution of 50 nm, a sixfold resolution improvement over that of confocal microscopy. High temporal resolution (<50 ms) is ensured by fast one-dimensional beam scanning. Individual trajectories of proteins translocating on DNA can thus be distinguished and tracked with high precision. We demonstrate our multimodal approach by visualizing the assembly of dense nucleoprotein filaments with unprecedented spatial resolution in real time. Experimental access to the force-dependent kinetics and motility of DNA-associating proteins at biologically relevant protein densities is essential for linking idealized in vitro experiments with the in vivo situation.

9164-42, Session 8

DNA origami based assembly of gold nanoparticle dimers for surface-enhanced Raman scattering

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Plasmonic sensors are extremely promising candidates for label-free single molecule analysis but require exquisite control over the physical arrangement of metallic nanostructures. We employ self-assembly based on the DNA origami technique[1] for accurate positioning of individual gold nanoparticles. Our innovative design leads to strong plasmonic coupling between two 40 nm gold nanoparticles reproducibly held with gaps of 3.3 ± 1 nm. This is confirmed through far field scattering measurements on individual dimers which reveal a significant red shift in the plasmonic resonance peaks, consistent with the high dielectric environment due to the surrounding DNA. We use surface enhanced Raman scattering (SERS)[2] to demonstrate local field enhancements of several orders of magnitude through detection of a small number of dye molecules as well as short single-stranded DNA oligonucleotides. This demonstrates that DNA origami is a powerful tool for the high-yield creation of SERS-active nanoparticle assemblies with reliable sub-5 nm gap sizes.

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9164-43, Session 8

Optical tweezers for free-solution label-free single bio-molecule studies

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Nanoaperture based trapping has developed as a significant tool among the various optical tweezer systems for trapping of very small particles down to the single nanometer range. The double nanohole aperture based trap provides a method for efficient, highly sensitive, label free, low cost, free solution single molecule trapping and detection. We use the DNH tweezer to understand biomolecular phenomena like protein unfolding, binding, structural conformation of DNA, protein-DNA interactions, and protein small molecule interactions. Statistical analysis of the trapping data is used for sensing the concentration and sizes of particles in a heterogeneous solution. The transient and Brownian fluctuation of the trapped particle is used to evaluate the efficiency of the trap and also further used to study the protein-binding interactions. The DNA binding interaction with a proteins is studied and quantitative evaluation of binding energies is shown. Extending this work to protein-interactions is of great interest for basic understanding of life function and for drug discovery applications

9164-44, Session 9

The electrostatic fluidic trap: a new approach to the spatial control and manipulation of matter at the nanometer scale

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We have demonstrated that single nanoscale objects in solution can be trapped in three dimensions in a fluidic nanoslit, without the application of external forces. Tailoring the geometry of the walls of the slit gives rise to an electrostatic free energy landscape, where local potential wells passively and stably confine single charged entities for long periods. As the method relies solely on net charge, objects that offer little dielectric contrast in a given medium, e.g. aqueous lipid vesicles in water, may easily be trapped by this method.

Relating the statistical properties of a trapped object's motion to a free energy calculation permits a direct measurement of its charge. Thus we predict the ability to measure single charge fluctuations on a particle carrying upto around 50 charges with millisecond time resolution by this method. Furthermore, in addition to spatial trapping, we have demonstrated that the geometry of the potential well can be used to control the orientiation of individual anisometric objects such as nanorods.

We further demonstrate the experimental realization of a levitation based nanophotonic switch that can be operated in both volatile and non-volatile modes. A plasmonic nanorod trapped in a bistable angular potential well and illuminated with light polarized along its long-axis fluctuates between two states – bright and dark. Application of an external electrical or optical field rapidly switches a single nanorod between the ON and OFF states, thus opening doors to soft-matter based digital photonic devices.

9164-45, Session 9

Metal/dielectrique structures fabrication using the photomechanical properties of azobenzene molecule

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Photochromic materials containing azobenzene derivatives exhibit spectacular photomechanical properties which allow controlling the formation of surface structures upon illumination in the chromophore visible absorption band. An impressive example is the significant light induced surface mass transport that can be observed on nano to micrometer scales.

Size and shape of the photo-induced surface pattern can be easily tailored over a large scale ranging from a few tens of nanometers up to several microns by controlling the projected optical pattern. These systems can be used in various technological applications, including holographic recording, photo-mechanics, diffraction optics, and micro- or nano-patterning.

Here, we use azobenzene containing films as photoactive layer for a one-step, non-contact and non-destructive lithography process. Using this technique we will show that, metal/dielectric hybrid 1D or 2D structures can be elaborated whose optical and mechanical properties can be controlled by light. Azobenzene molecules are inserted in PMMA or sol-gel matrices and deposited on glass substrate by spin-coating. Combining holographic patterning of the photochromic film with metal deposition under grazing incidence,, various surface patterns can be elaborated over large area. Considering that large absorption from the azo chromophore is a strong limitation for optical investigations, an original technique has been developed to remove completely the azobenzene chromophore while preserving the lithographic structuration of the films

Such hybrid system exhibits specific and intriguing optical and plasmonic properties. Both far field and near-field measurements are subsequently performed using angular resolved reflection spectroscopy and Scanning near-field microscopy (SNOM). Surface plasmon coupling and propagation can be tuned by adjusting the parameters of the structures at subwavelength scale. The experimental results are supported by electromagnetic modeling. Our results demonstrated a promising technique to reversibly elaborate nanostructured surface with tunable plasmonic properties.

9164-46, Session 9

Micron-scale motions from molecular-scale photochemistry

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Optical trapping and radiation forces allow light to directly exert forces on microscopic objects. An alternative approach is to transform light into chemical energy and use molecular motions to generate mechanical work. By assembling molecules into ordered crystals, sub-nanometer motions generated by photochemical reactions can be synchronized to produce displacements on the micron scale. By manipulating crystallization conditions, it is possible control the size and shape of crystals composed of photochemically reactive molecules. When these crystals are exposed to light, the aligned molecules undergo photochemical reactions that can drive dynamic shape changes of the crystal. If the photochemical reaction is reversible, the overall shape changes can also be reversible. Using a variety of methods, we prepare different classes of single crystal shapes, including nanowires, micro-ribbons, and micro-needles. Depending on the nature of the photochemical reaction, the shape of the crystal, and the orientation of the molecules within the shaped crystal, different types of motions can be induced by photoexcitation, including expansion, bending, twisting, and curling.[1] Micron and nanometer-scale structures that undergo well-defined shape changes when exposed to light could have applications as actuators or as components of nanoscale machines.

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9164-47, Session 10

On-chip photonic tweezers: integrated tools for optical trapping, self-assembly and micromanipulation

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In order to design future lab-on-a-chip, integrated optofluidic tools for trapping and manipulation of micro- and nano-objects are needed [1-4]. Following the example of free-space optical tweezers, this work aims at developing on-chip optical tweezers based on resonant photonic nanostructures. Optofluidic chips with integrated photonic tweezers are fabricated by adding a polydimethylsiloxane (PDMS) microfluidic channel on top of silicon-on-insulator (SOI) photonic "nanobeam" cavities [5]. The light resonance inside such photonic crystal cavities leads to a high spectral and spatial confinement of the electromagnetic field. This light confinement generates strong and localized near-field gradient forces that enables optical trapping and self-assembly of microparticles [6]. By coupling several cavities, spectral and spatial characteristics of resonant modes can be tailored in order to translate or rotate microparticles [7].

Particle tracking is used to study the trapping efficiency of the fabricated photonic tweezers. In the case of polystyrene microspheres 1µm in diameter, a lateral stiffness of 5 pN.µm-1 is measured, whereas it is found to decrease to 0.5 ± 0.1 pN.µm-1 along the waveguide axis. In addition, the trap is proved to resist to a lateral fluidic force of typically 10-1pN.

We also propose a new characterisation method based on the influence of a trapped particle on the cavity resonance. The guided signal transmitted by the cavity shows a different correlation time depending on the particle motion. This property is used to distinguish particles of different size and is investigated as a valuable integrated method to characterise the trapping efficiency of photonic tweezers.

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9164-48, Session 10

Investigations of the dynamics of resonantly trapped nanospheres in a hollow photonic crystal cavity

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Photonic crystal cavities (PhC) have the ability to confine light in very small mode volumes, allowing them to generate strong gradient forces. Particularly, bidimensional hollow photonic crystal cavities (HPhC) allow a strong overlap between the optical field gradient and the open space, allowing trapping at very low power level [1]. The interaction between the trapped object and the optical field generates remarkable features such as self-trapping and back-action [1]. Nanospheres with diameter less than 500 nm are trapped with less than 100 µW of guided power. These HPhC consist of silicon structures, immersed in water using a thin microfluidic layer on top, which allows us to image and record the position of the nanosphere in the cavity through the perturbation of the emitted cavity field.

Here we characterize the influence of the nanosphere size on its dynamics within the trap. Other parameters such as the material of the nanosphere, the Q-factor and the power that is coupled in the cavity are also investigated. The force exerted on the particle is derived and compared to the existing trapping techniques. Finally, we show the possibility to control the number of nanoparticles trapped in the cavity as well as to trap particles selectively regarding its size and index, which is cumbersome to achieve with standard optical tweezers.

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9164-49, Session 10

Inducing forced and auto oscillations in one-dimensional photonic crystals with light

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Optical tweezers is an example how to use light to generate a physical

force. They have been used to levitate viruses, bacteria, cells, and sub cellular organisms. Nonetheless it would be beneficial to use such force to develop a new kind of applications. However the radiation pressure usually is small to think in moving larger objects. Currently, there is some research investigating novel photonic working principles to generate a higher force. Here, we studied theoretically and experimentally the induction of electromagnetic forces in one-dimensional photonic crystals when light impinges on the off-axis direction. The photonic structure consists of a micro-cavity like structure formed of two one-dimensional photonic crystals made of free-standing porous silicon, separated by a variable air gap and the working wavelength is 633 nm. We show experimental evidence of this force when the photonic structure is capable of making auto-oscillations and forced-oscillations. We measured peak displacements and velocities ranging from 2 up to 35 microns and 0.4 up to 2.1 mm/s with a power of 13 mW.

9164-50, Session 11

New techniques in optical trapping and sensing

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Total internal reflection microscopy is a powerful technique for high resolution sensing near the interface of two dielectrics where a probe particle is allowed or made to move within the evanescent field region generated by total internal reflection. The probe particle, or cell, whatever is being imaged, scatters light by total internal reflection, which gives away its separation from the interface with nanometer precision if the intensity-position relation is known. Current methods for obtaining this relation are cumbersome: generally requiring either a replacement of the system in question with an approximately equivalent analog for which distances are known and controlled, or requiring even further knowledge of parameters such as viscosity, temperature, and mass of the particle. We propose and demonstrate an in situ calibration technique which acts on the actual experimental probe, under actual experimental conditions, with the use of a piezo-controlled optical tweezer, and demonstrate how this calibration fits into a TIRM (or other) measurement.

Additionally, anticipating the usual difficulties performing any kind of tweezing or sensing in the vicinity of a metallic surface due to back reflections and other optical field perturbations, we propose and demonstrate the effectiveness of an ultra-thin anti-reflection coating incorporating the metal itself. We show that in this design the metal interface is maintained, so desired surface chemistry, electrical and thermal conductivity, surface plasmon effects, etc. are generally unchanged, while field perturbations and measurement errors due to back reflections are largely eliminated. We hope this design will enable exciting research in an area which has so far not been extensively investigated.

9164-51, Session 11

Optical trapping of nanoscale plasmonic optical lattice in microfluidic environments

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Recent advances in optical manipulation have made it an ideal tool to create one, two, and three dimensional periodic optical potential. Such periodic potentials have found interesting technological and fundamental applications such as micro particle sorting and optical fractionation. Plasmon enhanced optical trapping techniques using metallic nanostructures can overcome the diffraction limits of far-field optical trap techniques and therefore permit trapping of nanoparticle with deep sub wavelength dimensions. Here we report the trapping of nanoparticles for a plasmon-enhanced two dimensional optical lattice. The density of the traps is ~20 times higher than previously reported optical lattice trapping based on holographic techniques. We observe the transport of (both single and multiple) nanoparticles over such an optical lattice. In addition, we will report the experimental progress toward integration of plasmon optical lattice with microfluidic chip. Such an integrated device allows the directional control of nano particles and provides a suitable platform for stochastic transport experiment such as nanoscale optical sorting. Compared to typical holographic techniques based on focusing optics, the plasmonic optical lattice requires much less optical power and is very suitable for lab-on-a-chip applications. Finally, the plasmonic optical lattices, when properly scaled down, will ultimately enable atomic physicists to study novel many-body physics problems.

9164-52, Session 11

Promoting optofluidic actuation of microparticles by plasmonic nanoparticles tagging

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The amplitude of optical forces on flowing dielectric microparticles can be actuated by coating them partially with metallic nanospheres and laser light exposition within the surface plasmon resonance. Here, optical forces on both pure silica particles and silica-gold raspberries are characterized within an optical chromatography setup by measuring the Stokes drag versus laser beam power. Results are compared to the Mie theory prediction for both pure dielectric particles and core-shell ones where the shell is described as a continuous dielectric-metal composite of dielectric constant determined from the Maxwell Garnett approach. The nice observed quantitative agreement demonstrates that radiation pressure forces are directly related to the metal concentration present at the microparticle surface and that nano-metallic objects increase indeed the magnitude of optical forces by several factors compared to pure dielectric particles of the same overall size, even at very low metal concentration. Behaving as “micro-sized nanoparticles”, the benefit of microparticles coated with metallic nanospheres is thus twofold: (i) to enhance optofluidic manipulation and transport at the microscale and, (ii) to increase sensing capabilities at the nanoscale, compared to separated pure dielectric particles and single metallic nanosystems.

9164-53, Session 11

Using dark field spectroscopy to measure dynamics and coupling of multiple nanoparticles in a single optical trap

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In the following study we investigate the coupling dynamics and self-organisation of multiple metallic nanoparticles held in a single gradient force optical trap. The use of dark field spectroscopy combined with optical tweezers allows us to probe the localized plasmon resonance (LSPR) spectrum of single and interacting nanoparticles, which provides a highly sensitive probe for sub-diffraction limited motion.

Interacting metallic nanoparticle within an optical field have been explored in a number of optical geometries [1-2] and have a demonstrated tendency to self-organize into particular stable configurations. In some instances these mutual scattering interactions can produce optical binding forces that much greater than the external trapping potential. For the standard gradient force trap resolving interacting particle dynamics is particularly challenging as particle separations are well below the diffraction limit of conventional optical imaging systems.

Near-field optical coupling between adjacent plasmonic particles leads to spectral changes that are dependent on inter-particle spacing as well as the orientation of the scattering objects with respect to the detection system. By trapping two particles independently within separate traps and then letting them combine allows both single LPSR spectra can be recorded before combining them in a single trap. The coupled-particle LSPR occurs at a frequency that is shifted from the single-particle LSPR frequency. Using a double well potential using two separate traps can also lead transient coupling where two-particle hop between coupled and uncoupled states.

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9164-54, Session 11

Dynamic plasmonic trapping and manipulation of metallic particles for SERS application

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We introduce a novel plasmonic tweezers for trapping and manipulating metallic particles and its application on Surface-enhanced Raman scattering (SERS). In the first part, we discuss the interaction mechanism between metallic particles and surface plasmons (SPs) in the plasmonic tweezers excited by a focused radially polarized beam. We show that metallic particles of nanometer to micrometer sizes can be attracted and trapped in such plasmonic tweezers instead of being repulsed by a conventional optical tweezers due to high scattering force. Through numerical analysis, we find that the resultant total force in the plasmonic tweezers is the result not of a stronger gradient force dominating an opposing scattering force, but instead of a dominant gradient force assisted by a weak scattering force acting in the same direction. Then we consider manipulating the metallic particles by modifying the incident beam properties in the plasmonic tweezers. The optical vortices (OV) are chosen to excite the plasmonic vortices and rotate particles in the plasmonic tweezers. We show that metallic particles in plasmonic vortices can be trapped and rotated in a certain radius according to OV's topological charge, due to the optical force provided by the orbital angular momentum (OAM). Finally, we introduce the application of the plasmonic tweezers in SERS. By trapping and dragging a single gold nanoparticle with the plamonic tweezers, we demonstrated a dynamic single-particle-film SERS system, which produces a SERS enhancement factor of ~109, and therefore provides a promising approach to controllable SERS detection and imaging.

9164-55, Session 11

Photothermal heating of silicon nanowires in a single-beam laser trap

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A theoretical model is developed here in tandem with single-beam laser trapping experiments to elucidate the effects of the numerous thermal, optical, and geometric parameters that affect internal temperature distributions within finite nanowires (NWs) during laser irradiation. Analytical solutions to the heat-transfer equation are presented to predict internal temperature distributions within individual nanowires based on numerical calculations of the internal electromagnetic heat source. A new method to extract temperatures of trapped particles during single-beam laser trapping experiments is presented and is used to measure photothermal heating of silicon NWs (SiNWs). Silicon has received little attention to date for photothermal heating applications due to its indirect band gap and low absorption coefficient in the near-infrared tissue-transparency window. We also show that phosphorus ion implantation may be used to increase the optical absorption of SiNWs, leading to significant heating to temperatures greater than 42 °C in an aqueous environment at an irradiance of 3 MW/cm2. Experimental observations of photothermal heating agree well with theoretical predictions. Calculations for comparison with amorphous carbon NWs reveal significantly greater heating effects, as well as internal radial gradients not observed for SiNWs.

9164-56, Session 11

Anomalous dynamic behaviour of optically trapped high aspect ratio nanowires

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In the following presentation we experimentally investigate apparent anomalous dynamic behaviour of high aspect ratio nanowires held in a single gradient force optical tweezers. Power spectrum analysis performed on the stochastic trajectory of the optically trapped nanowires indicates that, under certain circumstances, nanowires undergo oscillatory motion analogous to underdamped systems. This motion is characterised by a broad resonance peak of the order of 1 kHz. Auto-correlation measurements confirm a pronounced ringing signature on the millisecond time scales. We investigate the dependence of the peak frequency as a function of optical trapping powers, polarisation, nanowire length and trapping height above the coverslip. We discuss the emergence of resonant behaviour in the context of different possible driving mechanisms, including hopping between local minima and coupling between translation and rotational motion, and first-order non-conservative behaviour arising from the low symmetry of the nanowires.

9164-57, Session 11

Optical trapping with pillar bowtie nanoantennas

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Plasmonic nanoantennas make effective optical tweezers, owing to their characteristic field enhancement and confinement properties which produce large near-field intensity gradients. The trapping dynamics of plasmonic nanotweezers are strongly affected by their resonant optical absorption, which can produce significant heating and induce rapid convective flows in the surrounding fluid medium. We here consider a new class of plasmonic nanotweezers based on an elevated bowtie nanoantenna (BNA) geometry, whereby BNAs are suspended on optically transparent, 500-nm tall silica pillars. We discuss how the plasmonic properties of these pillar-BNAs (p-BNAs) can be manipulated in large areas of 80 x 80-micron or at the level of an individual p-BNA using either a low-power input optical beam or electron-beam, respectively. This modification in local plasmonic properties is expected to result in a much more complex optical trapping landscape. We also find that the temperature increase in the p-BNAs is more than 10x higher than in comparable substrate-bound structures (for the same input intensity), in which the substrate acts as a heat sink that mitigates temperature increase, and we investigate the role of this enhanced thermo plasmonic heating on plasmonic trapping dynamics.

9164-58, Session 12

Active matter transport on complex landscapes

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Systems containing self-motile or self-driven particles are commonly referred to as active matter systems, and include swimming bacteria, crawling cells, flocks of animals, and even pedestrian motion. Recently a number of experimental groups have successfully created non-biological active matter with techniques such as light-activated colloids. These systems can exhibit a wealth of nonequilibrium behaviors including clustering, flocking, anomalous diffusion, and pattern formation. Existing studies have generally focused on active matter interacting with a smooth substrate; however, in the wild, active biological matter generally moves through complex environments. Additionally, many applications of colloidal active matter systems will require the particles to interact with a disordered environment. Many studies of non-active colloids examined the effect on the colloidal ordering or dynamics of a periodic or disordered landscape created using optical trapping techniques. Similar techniques could be employed to generate complex substrates for active matter systems. Here we show how the introduction of a random landscape can shift the onset of the clustering phase of active matter systems. In the absence of a substrate, increasing the activity of the system normally increases the mobility; however, when obstacles are present in the landscape, we find that there is an optimal activity level at which the highest particle mobility can be achieved. These results suggest that biological systems may have optimized their activity level in order to move through complex environments.

9164-59, Session 12

Targeted delivery of colloids by swimming bacteria

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The possibility of exploiting motile microorganisms as tiny propellers represents a fascinating strategy for the transport of colloidal cargoes. However, delivery on target sites usually requires external control fields to steer propellers and trigger cargo release. The need for a constant feedback mechanism prevents the design of compact devices where biopropellers could perform their tasks autonomously. Here we show that holographically fabricated three- dimensional microstructures can define accumulation areas where bacteria spontaneously and efficiently store colloidal beads. The process is stochastic in nature and results from the rectifying action of an asymmetric energy landscape over the fluctuating forces arising from collisions with swimming bacteria. As a result, the concentration of colloids over target areas can be strongly increased or depleted according to the topography of the underlying structures. Besides the significance to technological applications, our experiments pose some important questions regarding the structure of stationary probability distributions in non-equilibrium systems.

9164-60, Session 12

Collective behavior of the optically driven particles on a circular path

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Hydrodynamic interaction is crucial for micrometer-sized objects such as colloids and microorganisms in liquids. Various interesting collective motions including synchronization and rhythmic motion have been reported recently. In this paper, we report experimental study on the collective motion of optically driven particles on a circular path. The micrometer-sized silica colloidal particles are trap on a ring and are forced to rotate with a constant angular velocity by optical vortex which has been realized by a holographic optical tweezers. The characteristic rhythmic motion and the formation of dynamic stable clusters have been observed depending on the number of the particles on a ring and their size.

In the case of the system containing the same-sized particles, a doublet becomes the most stable. When the number of the particles on the ring is even, each of two forms doublet and rotates at constant velocity with almost equal space. On the other hand, when the number of the particles is odd, the formation and decomposition of longer clusters occurs and this induces rhythmic motion. In the case of the system containing different-sized particles, only one or some longer clusters are selectively induced and temporally stable. The final clusters are only determined by the initial arrangement of the particles. These experimental finding are well explained by the simulation with Stokesian hydrodynamics.

9164-61, Session 12

Hydrodynamic synchronisation in arrays of optically controlled rotors *(Invited Paper)*

Simon Hanna, Luke J. Debono, Stuart J. Box, Stephen H. Simpson, Univ. of Bristol (United Kingdom); David B. Phillips, Univ. of Glasgow (United Kingdom)

Hydrodynamic coupling plays a vital role in the coordinated beating of cilia and flagella, and is important for the design of future microscopic machines, artificial swimmers and pumps. In this paper we present a combined theoretical and experimental study of synchronisation effects in two-dimensional arrays of rigid rotors. The rotors are fabricated using 2-photon polymerisation, and are held in an array of optical traps generated using holographic optical tweezers. Rotation is induced by introducing asymmetry either into the optical fields, e.g. with Laguerre-Gaussian beams, or into the shape of the particles. Both the symmetry of the particles and the symmetry of the lattice may be varied, as may the directions of rotation e.g. co-rotating or counter-rotating. The strength of the hydrodynamic coupling, and the resultant synchronisation, is found to depend on all of these factors. Intriguingly, specific couplings are also observed between distant, but symmetrically related, rotors. The mechanisms of phase-locking and synchronisation will be explored and comparisons drawn between theory and experiment.

9164-62, Session 12

Optical trapping and lifting of plasmonic Janus microparticles

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Janus particles with a plasmonic and a dielectric face have opened up a wide field of applications. Heat generated due to strong absorption of radiation by the metal part can induce an asymmetrical thermal gradient in the environment, which can be employed for self-propulsion in a liquid media. Here we combine this optothermal self-propulsion effect of Janus particles with our methodologies [1, 2] to manipulate gold nanoparticles in focused laser beams.

We explore the balance of optical and thermal forces acting on gold/silica Janus microparticles which are optically trapped in an aqueous medium. By varying the trapping laser power, we see a shift in the particle position as it finds an equilibrium point between the experienced optical and thermal forces, leading to self-propulsion. Lowering laser power leads to relaxation of the Janus particle from this elevated state. Finally, we optically control the distance between a Janus particle and other micro- and nano-objects based on this novel concept. This photonic micron-scale "elevator" might find future applications in thermal force studies as well as in optical micromanipulation experiments.

[1] S. Nedev, A. S. Urban, A. A. Lutich, J. Feldmann, Nano Lett. 11, 5066 (2011).

[2] A. Ohlinger, A. Deak, A.A. Lutich, J. Feldmann, PRL 108, 018101 (2012).

9164-63, Session 12

3-axis digital holographic microscopy for high speed volumetric imaging

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Digital Holographic Microscopy allows to numerically retrieve three dimensional information encoded in a single 2D snapshot of the coherent superposition of a reference and a scattered beam. Since no mechanical scans are involved, holographic techniques have a superior performance in terms of achievable frame rates. On the other hand direct numerical reconstructions usually lead to a poor axial resolution. Here we show that overlapping the three numerical reconstructions obtained by tilted red, green and blue beams results in a great improvement over the axial resolution and sectioning capabilities of holographic microscopy. A strong reduction in the coherent background noise is also observed when combining the volumetric reconstructions of the light fields at the three different wavelengths. We discuss the performance of our technique with two test objects: an array of four glass beads optically trapped along the optical axis and a swimming rod shaped E. coli bacterium.

9164-64, Session 13

Maxwell´s demon with optical tweezers

Regina K. Schmitt, Heiner Linke, Jonas Johansson, Lund Univ. (Sweden)

Ever since Maxwell proposed his Gedankenexperiment in 1871 it has had great impact in theoretical physics but its experimental realization is after 250 years still an ongoing challenge. Optical tweezers have proven to be a very powerful tool in various fields where biophysics is the most prominent. In this investigation we use optical tweezers in order to realize a Maxwell´s Demon. A major step in that direction has already been undertaken by Toyabe et al [Nature Physics 6 (2010) 988]. However, our approach offers the opportunity to investigate a Maxwell´s Demon in its purest form, where the effect of applied work can be avoided. Our system is based on a feedback controlled optical line trap, realized using an acousto optical deflector, restricting the thermal motion of a silicon bead to a linear potential under the influence of a constant external force. Depending on the particles position which is monitored with a CCD camera, potential barriers can be set up at specific predetermined positions. Both the positions and shape of the barrier can be varied. Thus it allows to gradually investigate the interplay of "power stroke" and work extracted from the heat bath. Furthermore our experiments can be analyzed with a rather simple theoretical model. The gained knowledge on these energy conversion processes may lead to a better understanding not only of thermodynamic processes but also of the functionality of molecular motors.

9164-66, Session 13

Spatial measurement of spurious forces with optical tweezers

Ignacio A. Bordeu, Univ. de Concepción (Chile); Giovanni S. Volpe, Bilkent Univ. (Turkey); Juan Pablo Staforelli, Univ. de Concepción (Chile)

The study of diffusion in a crowded and complex environment, such as inside a cell or within a porous medium, is of fundamental importance for science and technology. Combining blinking holographic optical tweezers and sub-pixel video microscopy permits one to study Brownian motion in confined geometries. In this work, in particular, we have studied the Brownian motion of two colloidal particles interacting hydrodynamically with each other. The proximity between the two microspheres induces a space-dependence in the particles diffusion coefficient and, therefore, a spurious drift. We measure this drift and evaluate the magnitude of the spurious force associated with it. We present the optoelectronic tools employed in the experiment and we discuss the experimental results.

9164-67, Session 13

Einstein's osmotic equilibrium of colloidal suspensions in conservative force fields *(Invited Paper)*

Daniel H. Ou-Yang, Jinxin Fu, Lehigh Univ. (United States)

Predicted by Einstein in his celebrated 1905 paper on Brownian motion, and experimentally demonstrated by Perrin and won him Nobel Prize in Physics in 1926, colloidal particles in suspension reach osmotic equilibrium under gravity. The shape of the number density profile depends on particle mass, gravitational acceleration, temperature and the interactions between the particles. Also, in 1926, Theodore (The) Svedberg won Nobel Prize in Chemistry for his "work on disperse systems" leading to the determination of hemoglobin molecular weight. We show Einstein's equation for osmotic equilibrium can be applied to colloids in conservative force fields other than gravity. We demonstrate experimentally that coupling between quasi-conservative force of light and nanoparticles in suspensions as well as interactions between colloidal nanoparticles can be determined by the particle number density distributions alone. The former can be determined from the Boltzmann distribution of the particle number density for dilute solutions when interactions between the particles are negligible. Once the optical force field is determined, interactions between the interacting particles or more specifically, the osmotic equation of state of the colloids can be determined from the known force field. An implication of the idea presented here is the potential of generalization from gravity to other conservative force fields, and from colloidal systems to macromolecular solutions to active colloids.

9164-68, Session 14

Micro-rheology and interparticle interactions in aerosols probed with optical tweezers

Jonathan P. Reid, Rory M. Power, Chen Cai, Stephen H. Simpson, Univ. of Bristol (United Kingdom)

Using optical tweezers for micro-rheological investigations of a surrounding fluid has been routinely demonstrated. In this work, we will demonstrate that rheological measurements of the bulk and surface properties of aerosol particles can be made directly using optical tweezers, providing important insights into the phase behaviour of materials in confined environments and the rate of molecular diffusion in viscous phases.

The use of holographic optical tweezers to manipulate aerosol particles has become standard practice in recent years, providing an invaluable tool to investigate particle dynamics, including evaporation/condensation kinetics, chemical aging and phase transformation. When combined with non-linear Raman spectroscopy, the size and refractive index of a particle can be determined with unprecedented accuracy (<+/- 0.05%). Active control of the relative positions of pairs of particles can allow studies of the coalescence of particles, providing a unique opportunity to investigate the bulk and surface properties that govern the hydrodynamic relaxation in particle shape. In particular, we will show how the viscosity and surface tension of particles can be measured directly in the under-damped regime at low viscosity. In the over-damped regime, we will show that viscosity measurements can extend up close to the glass transition, allowing measurements over an impressive dynamic

range of 12 orders of magnitude in relaxation timescale and viscosity. Indeed, prior to the coalescence event, we will show how the Brownian trajectories of trapped particles can yield important and unique insights into the interactions of aerosol particles.

9164-69, Session 14

The study of thin films on solid aerosol particles using optical trapping and Mie scattering from a broadband white LED

Stephanie H. Jones, Univ. of London (United Kingdom); Andrew D. Ward, Rutherford Appleton Lab. (United Kingdom); Martin D. King, Univ. of London (United Kingdom)

A counter-propagating optical trap has been used to study the oxidation of thin organic films on the surface of solid particulates levitated in air. Micron sized silica and polystyrene spheres, have been trapped in air between opposed 1064 nm laser beams, and illuminated with a broadband white LED. Backscattered light from the trapped particle was collected to obtain a Mie spectrum over the 480-700 nm wavelength range and this was used to determine particle radius and wavelength dependent refractive index (Jones et al., 2013). The trapped particle was coated using a flow of organic vapour and the resultant thin film oxidised by introducing ozone, a common atmospheric oxidant, into the gaseous medium. Resonance positions in the Mie spectrum were monitored with time and analysed using a coated sphere model. Analysis indicated initial film formation followed by film oxidation on the introduction of ozone. Currently, film oxidation is associated with a decrease in film thickness, however, this observation is complicated by the optical properties of products formed.

Whilst thin films are believed to form naturally on atmospheric aerosols (Tervahattu et al., 2002), a debate remains as to whether the organic component completely coats the aerosol surface or partially engulfs it. Such films are readily oxidised in the atmosphere causing a change in aerosol properties and knowledge of aerosol properties is required to understand their effect on the climate. The use of optical trapping combined with Mie spectra acquisition to study and characterise coated solid particulates is therefore an important step in atmospheric science.

9164-70, Session 14

Aerosol optical chromatography and measurements of light extinction by single particles

Jonathan P. Reid, Bernard J. Mason, Michael I. Cotterell, Thomas C. Preston, Andrew Orr-Ewing, Univ. of Bristol (United Kingdom)

To resolve some of the significant uncertainties in the impact of aerosols on global climate, new tools are required to probe light scattering and absorption by aerosol particles. Ideally, such tools should allow direct measurements on individual particles over extended periods of time, providing data to better constrain the optical properties of aerosol, how they depend on the environmental conditions (relative humidity and temperature) and how they change with time. Here, we will present a new technique using a combination of a Bessel beam to manipulate individual particles and cavity ringdown spectroscopy for ultrasensitive measurements of the optical extinction.

We will show that particles can be spatially separated along the propagation direction of a Bessel beam according to their size and refractive index when confined by a Bessel beam core and a counter-propagating gas flow, referred to as optical chromatography. The time-dependent position of a particle will be shown to be a consequence of the differing size dependencies of the forces arising from Stokes drag and radiation pressure. We will also show that particles captured in a Bessel beam can be moved in and out of an optical cavity formed by two highly reflective mirrors. The time constant for the ringdown in light coupled within the cavity can then be used to measure the optical cross-section of the individual particle with extremely high accuracy. An individual particle can be captured indefinitely and its change in optical cross-section measured with change in environmental conditions.

9164-71, Session 14

Microparticle conveyor belt and particle-based sensing in hollow-core photonic crystal fiber

Tijmen G. Euser, Oliver A. Schmidt, Max-Planck-Institut für die Physik des Lichts (Germany); Dmitry S. Bykov, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Philip St. John Russell, Max-Planck-Institut für die Physik des Lichts (Germany)

We review our recent work on microparticle manipulation in air-filled hollow-core photonic crystal fiber (HC-PCF). First, we show that a coherent superposition of co-propagating spatial modes, balanced by a backward-propagating fundamental mode, creates a series of trapping positions spaced by half the beat-length between the forward-propagating modes (typically 1 mm). The system allows a trapped microparticle to be moved along the fiber by continuously tuning the relative phase between the two forward propagating modes. This mode-based “optical conveyor belt” combines long range transport of microparticles with a positional accuracy of ~1 µm [1]. Recently, we also demonstrated that microparticles can be used as microscopic sensors that probe, for instance, the electric field strength along a HC-PCF [2]. Here, the optical conveyor is used to position a charged microparticle along the fiber. Transverse electric fields displace the microparticle, the resulting change in transmitted power is found to be linear with fields in the 0.1-50 kV/m range, with a flat frequency response from 0.01 to ~1 kHz. In a first test, the field pattern near a multi-element electrode was resolved with a spatial resolution of 1 mm. This unique “flying particle” sensor allows electric field mapping over long distances and is suitable for otherwise inaccessible or harsh environments [2].

[1] O. A. Schmidt et al., “Mode-based microparticle conveyor belt in air-filled hollow-core photonic crystal fiber,” Opt. Express 21, 29383-29391 (2013).

[2] D. S. Bykov et al., “Electric field sensing with high spatial resolution via a charged “flying particle” optically guided inside hollow-core PCF, “ (submitted to: Optical Fiber Sensors 23).

9164-73, Session 15

Ordering of colloids with competing interactions on quasi-one-dimensional periodic substrates

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There have been numerous studies of colloids interacting with both one- and two-dimensional periodic substrates, showing the occurrence of order-disorder transitions as well as dynamical phenomena such as depinning transitions and frictional effects. Existing studies focused on systems in which the colloid-colloid interaction potential is strictly repulsive; however, there are many other possible colloidal interactions including potentials that combine attractive and repulsive components. In the absence of a substrate, particles with competing interactions can exhibit transitions among crystal, stripe, bubble, clump and void states, each of which can be ordered or disordered. Here we investigate a system of colloids with a long range repulsive and short range attractive interaction potential in the presence of periodic one-dimensional substrates. The substrates stabilize colloidal orderings that do not occur in the absence of a substrate. For strong substrates, the particles adopt a one-dimensional periodic stripe pattern, and as the substrate strength is reduced, we observe the formation of periodically arranged kink structures. For weak substrates, stripes with a different orientation appear. We discuss the dynamics of these states under an external drive and show that effective pinning or friction in the moving states is correlated with transitions observed in the pinned state.

9164-74, Session 15

Hybrid optical and acoustic force based sorting

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Optical and acoustic micromanipulation have both proven to be capable of label free cell sorting. This paper discusses a hybrid optical/acoustic sorting approach designed to meet the demands for quality control in the industrial scale production of stem cell derived RBCs, where non-fully differentiated stem cells are removed from fully differentiated erythrocytes.

Passive sorting using optical forces has been used in the past for sorting cells, including RBCs. In those approaches an optical gradient force [MacDonald, Nature 2003] or radiation pressure [Hart, Applied Physics Letters 2003] is typically set in opposition to a fluid drag, leading to particle motion which is size, shape and refractive index dependent. In this paper we discuss sorting which arises from the opposition of an acoustic gradient force against either an optical gradient force or optical radiation pressure.

We have investigated the effect of deflecting particles out of the acoustic standing wave nodes - which both levitates particles/cells and laterally confines them - using vertical or lateral optical deflection where the optical force is produced either by a gradient force in an optical lattice, or a radiation pressure from a weakly focussed Gaussian beam. If and by how much a particle is deflected depends on the interaction strength with both the optical and acoustic fields, hence giving hybrid optical and acoustic sorting.

By combining optical and ultrasonic forces we have produced a system with potentially greater selectivity, able to sort optically by size, shape and refractive index; or acoustically by compressibility and density.

9164-75, Session 15

Advanced optical particle manipulation on an integrated optofluidic platform

Holger Schmidt, Kaelyn D. Leake, Damla Ozcelik, Univ. of California, Santa Cruz (United States); Brian S. Phillips, Aaron Hawkins, Brigham Young Univ. (United States)

We will review recent progress in on-chip particle manipulation on a liquid-core waveguide optofluidic platform. We will discuss, particle trapping techniques as well as optical particle sorting.

9164-76, Session 15

Real-time and high-throughput mechanical phenotyping of suspended cells

Oliver Otto, Philipp Rosendahl, Stefan Golfier, Alexander Mietke, Salvatore Girardo, Technische Univ. Dresden (Germany); Stefano Pagliara, Ulrich F. Keyser, Univ. of Cambridge (United Kingdom); Jochen R. Guck, Technische Univ. Dresden (Germany) and Univ. of Cambridge (United Kingdom)

The mechanical properties of cells have been emerging as label-free, inherent marker of biological function and disease. Concerted utilization has so far been hampered by the availability of a convenient and robust measurement technique. We report the development and characterization of a microfluidic system for mechanical single cell classification in real-time with analysis rates of several hundred cells per second.

A cell suspension is driven through the constriction zone of a microfluidic chip resulting in cell deformation due to hydrodynamic interactions only. Our custom-built image processing software is capable of performing image acquisition, image analysis and data storage on the fly allowing for mechanical phenotyping of several hundred cells per second in real-time.

The ensuing deformations can be described by an analytical hydrodynamic model. Experiments based on our novel technology with different cell types are in agreement with results obtained with atomic force microscopy and optical stretcher. Our method allows continuous mechanical phenotyping of large and heterogeneous cell populations with a throughput previously only known from flow cytometry.

9164-77, Session 15

Optical deformation of red blood cells trapped on a narrow waveguide

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The evanescent field of an optical waveguide can trap and propel red blood cells along the waveguide. A method to optically squeeze red blood cells (RBCs) using an optical waveguide is reported. We demonstrate that the intensity gradient of the evanescent field at the edge of narrow waveguides (1-3 µm) can be used to squeeze a blood cell. The RBCs are squeezed to a size comparable to the waveguide width. When the laser is switched on the cell is attracted towards the waveguide and is held in place. Subsequently, the part of the cell not on the waveguide is pulled in across the waveguide. The result is a cell (7-8 µm in diameter) squeezed down to a significantly smaller width (typically 3 µm). The cell regains its original shape when laser is switched-off. A tapered waveguide (8 µm to 1 µm) was used to bio-mimic the sudden change in the stress level acting on RBCs encountering micro-capillaries during blood circulation. Optical forces and pressure distributions on the cells are numerically computed and are used to explain the squeezing process. The proposed method is used to monitor minute loss of blood deformability during blood storage lesion. The method was found to be highly sensitive and a fast and significant loss of blood deformability during storage was found. Squeezing of red blood cells on waveguide works simultaneously on several cells making the method suitable for monitoring cell population.

9164-78, Session 15

Optoelectronic cell lysis

Steven L. Neale, Christian Witte, Alasdair W. Clark, Julien Reboud, Jonathan M. Cooper, Univ. of Glasgow (United Kingdom)

In this paper we show how the electrical lysis of cells can be controlled through the use of an optoelectronic device. We describe how the lysis process is affected by the size and shape of the cell, which enables the specific selection of individual cell types amongst a mixed population, as well as by the geometry of the device and the light patterns used.

Cell membranes consist of a phospholipid bi-layer which is transfixed by membrane proteins, some of which form channels allowing the membrane to be selectively permeable to ions. By controlling these

channels, the cell can keep the voltage across its membrane (the transmembrane potential) constant. For living cells, the membrane is a good electrical insulator to applied electrical fields of low frequencies with its impedance only dropping at higher frequencies.

When sufficient voltage is applied to a cell, however (on the order of 100s of mV across its membrane), pores form in the membrane and if the voltage is further increased, this electroporation turns into electrical lysis as the pores enlarge and merge together. Here we examine the factors that affect this process within an optoelectronic device that allows us to precisely control the fields the cells experience, through the creation of light induced "virtual electrodes". We show how the size, shape and position of the cell within different device geometries affect these processes. We demonstrate how this can be used to gain access to intracellular contents including organelles and discuss how this can be used for analysis.

9164-79, Session 15

Pulsed laser activated cell sorter (PLACS) for high-throughput fluorescent mammalian cell sorting

Yue Chen, Ting-Hsiang Wu, Univ. of California, Los Angeles (United States); Aram Chung, Rensselaer Polytechnic Institute (United States); Michael A. Teitell, Dino Di Carlo, Pei-Yu E. Chiou, Univ. of California, Los Angeles (United States)

We present a Pulsed Laser Activated Cell Sorter (PLACS) realized by exciting laser induced cavitation bubbles in a PDMS microfluidic channel to create high speed liquid jets to deflect detected fluorescent samples. The bubble expands to largest diameter in a few microseconds and has internal pressure of tens of MPa. This ultrafast switching mechanism has a complete on-off cycle of less than 20 µsec with a small liquid perturbation volume. Two schemes are used to achieve 3D focusing. One utilizes multilayer PDMS channels with added vertical pathways to achieve 3D hydrodynamic focusing. The 3D sheath flow focusing offers accurate timing control of fast (2 m/sec) passing particles or cells, enabling high purity sorting at high throughput. 3D PLACS is capable of sorting at 11,000 cells/sec with >95% purity or at 45,000 cells/sec with 45% purity within a single channel.

We also demonstrate integration of PLACS with 3D sheathless inertial focusing, which uses 10 times lower initial concentration cell samples than that in sheath-based PLACS in order to avoid severe dilution effects from high volume sheath flows at the same throughput. Fluid inertia and secondary flows induced by stepped microchannels are used to focus samples in 3 dimensions. An expansion chamber will enlarge the inter-particle distance of closely positioned particles. The PLACS with 3D sheathless inertial focusing is capable of sorting at 10,000 particles/sec with >90% sort purity and 6,000 cells/sec with >80% sort purity.

9164-94, Session PWed

Dynamics of two atoms undergoing collisions and molecule formation in an optical microtrap

Yin Hsien Fung, Pimonpan Sompet, Alicia V. Carpentier, Mikkel F. Andersen, Univ. of Otago (New Zealand)

Photo-association provides a promising route to the ability to construct individual molecules in particular quantum states. We study the dynamics of atoms in a far off resonance optical trap when exposed to laser light that induces molecule formation and light-assisted collisions. We implement the idealised collision experiment in which only two atoms are present in the trap so that we can observe individual atom loss events and their evolution when exposed to red-detuned light. Due to the simplicity of the system (with just two atoms in the microtrap) we can directly simulate the two-atom dynamics, thereby revealing detailed insight into it. We find that light-assisted collisions can result in only one of the colliding partners being expelled from the optical trap, besides the pair loss often assumed. Generally both channels are present; but which is more likely depends on the dynamics of the atoms in the trap under the influence of laser cooling. This finding highlights the importance of studying microscopic processes at the individual event level as it allows us to discriminate between different outcomes of event. Finally, the existence of collisional single atom ejection allows us to exceed the 50% isolation efficiency of individual atoms previously reported when using red-detuned light-assisted collisions. The onset of other loss mechanisms still limits our single atom loading efficiency to 63%.

9164-95, Session PWed

Computational toolbox for optical tweezers in geometrical optics

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Optical tweezers have found widespread application in many fields, from physics to biology. Here, we explain in detail how optical forces and torques can be described within the geometrical optics approximation and we show that this approximation provides reliable results in agreement with experiments for particles whose characteristic dimensions are larger than the wavelength of the trap- ping light. Furthermore, we provide an object-oriented software package implemented in MatLab for the calculation of optical forces and torques in the geometrical optics regime: OTGO - Optical Forces in Geometrical Optics. We provide all source codes for OTGO as well as the documentation and code examples – e.g., standard optical tweezers, optical tweezers with elongated particle, wind- mill effect, Kramers transitions between two optical traps – necessary to enable users to effectively employ it in their research and teaching.

9164-96, Session PWed

Micro-particles self-arrangement in shapeable counter-propagating beams

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The very first experiments with light trapping of particles were performed by A. Ashkin using counter propagating laser beams. We use the geometry of counter-propagating beams but enhanced with spatial light modulator to shape the intensity profile and number of counter-propagating beams. We observed self-arrangement of sub-micrometer size particles into colloidal waveguides long tens of micrometers, we investigated particles positions and tested theoretical models describing their behaviour.

9164-97, Session PWed

Rapid fabrication of polymeric micro lenses for optical fiber trapping and beam shaping

Ana Rita S. Rodrigues Ribeiro, Raquel B. Queirós, INESC TEC (Portugal); Carole Ecoffet, Ecole Nationale Supérieure de Chimie de Mulhouse (France); Olivier Soppera, Institut de Sciences des Matériaux de Mulhouse (France); Abel González Oliva, Instituto de Tecnologia Química e Biológica (Portugal); Ariel R. Guerreiro, Univ. do Porto (Portugal) and INESC TEC (Portugal); Pedro A. S. Jorge, INESC TEC (Portugal)

The ability to trap and accurately manipulate either cells or dielectric particles without physical contact is a key aspect of optical tweezers. In 1995 one of the first single optical fiber tweezer was proposed by

M. Ikeda, and since then several others have been developed. Through fiber-end micro machining/fabrication technologies, distinct structures and designs have been investigated to use optical fibers as trapping instruments. However, most of them do not allow an accurate control of the produced lenses, are time consuming and sometimes expensive.

In this work, we report a new type of optical fiber tweezers based on polymeric micro-lenses. The lenses are achieved by means of a low cost and fast fabrication process, using an in-fiber photo-polymerization technique. The polymerization radiation is guided towards the fiber tip creating a polymeric waveguide, by self-guiding effect. The method allows tailoring the geometry of the tip (eg. curvature radius, length) by adjusting fabrication parameters such as the exposure time, the composition of the polymer or the power of the polymerization laser. In addition, more complex shapes can be fabricated by exploring modal effects at the polymerization and trapping wavelengths. Therefore, using a simple setup it is possible to fabricate optical fiber micro tips for different applications such as trapping, beam shaping and patterned illumination. The design and fabrication of the micro lenses are supported by 3-dimensional numerical simulations, using the Finite Differences Time Domain method.

9164-98, Session PWed

Generation of shock waves in a medium with absorbing particles

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This work is dedicated to the generation of shock waves in a disperse medium with absorbing particles using continuous laser radiation.

In our investigations we utilized the mechanism of explosive boiling, when an explosive evaporation of the liquid occurs. For carrying out the experiments we used continuous laser radiation of low power and the aqueous suspension of black pigment particles.

It turned out that the emergence of shock waves and corresponding medium blooming while focusing laser radiation on the cell with the disperse medium is periodic in time and runs the following way: the particles absorb radiation, heat themselves, heat the water, the water boils, cavitation occurs, a shock wave is generated, medium blooming takes place, and then the particles occupy the bloomed volume and absorb radiation again.

As the result of the experimental investigation it was found that the illuminating beam diameter growth at the constant laser power results in the decrease of the signals' modulation frequency, improving their stability and increasing their amplitudes. In its turn, the decrease of the signal's modulation frequency is caused by the growth of time, which is needed for heating the medium to the critical temperature of cavitation. Improving the stability and the increase of optical and acoustic signals' amplitudes take place due to the growth of the medium volume, and hence the number of pigment particles that participate in cavitation.

The results of these investigations will become the basis for the diagnostic technique of absorbing disperse media.

9164-99, Session PWed

Viscoelasticity measurements inside liposomes

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Microrheology?the study of the behavior of fluids on the microscopic scale?has been and continues to be one of the most important areas of study which can be applied to characterize the behaviour of biological fluids.

It is extremely difficult to make rapid measurements of the viscoelastic properties of the interior of living cells. Liposomes are widely used as model systems for studying different aspects of cell biology as they closely mimic cellular membranes. We propose to develop a microrheometer, based on real-time control of optical tweezers, to investigate the viscoelastic properties of the fluid inside liposomes. This will give a greater understanding of the viscoelastic properties of the fluids inside cells.

In our experiment, the liposomes are prepared by a modified electroformation procedure. Instead of originally preparing a dry lipid film deposited on an electrode, we use hydrogel stamps to prepare lipid deposits. During the procedure of lipid formation in which we produce a large number of monodisperse giant liposomes, the birefringent microspheres are added to buffer solution and are encapsulated inside liposomes. By rotating the vaterite inside a liposome via spin angular momentum, the optical torque can be measured by measuring the change of polarization of the transmitted light, which allows the direct measurement of viscous drag torque since the optical torque is balanced by the viscous drag

We present an initial feasibility demonstration of trapping and manipulation of a microscopic vaterite inside a liposome. The applied method is simple and can be extended to sensing within living cells.

9164-100, Session PWed

natural user interface as a supplement of the holographic Raman tweezers

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Holographic Raman tweezers (HRT) manipulates with microobjects by controlling the positions of multiple optical traps via the mouse or joystick. Several attempts have appeared recently to exploit touch tablets, 2D cameras or Kinect game console instead. Natural User Interface (NUI) is a progressive way of a man-machine communication based on gestures, hand and body pose, speech etc.

Proposed method accepts inputs from various NUI devices and sends them to HRT using specific network protocol messages (OSC). We have tested 3D cameras (Kinect, Leap Motion, Creative Gesture Camera, MyGaze) detecting 3D coordinates of fingertips, hand joints, head, eye gaze vector etc. System also recognizes voice commands and gestures sending them to HRT which subsequently controls the positions of trapping beams, micropositioning stage and the acquisition system of Raman spectra. This, of course, required adaptation of HRT firmware to interpret received OSC messages. We have proposed also an indirect control alternative which doesn't require any modification of existing HRT firmware because the software simulates mouse and keyboard messages. Any HRT should accept simulated messages by the same way as these coming from the real mouse or keyboard.

Our system does not try to replace the traditional control of HRT but to extend it - e.g. mouse in one hand combined with gestures of the second hand is possible. We present various modes of operation proper for specific tasks. Proposed methods not only make manual control of HRT more efficient but they are also a good platform for its future semi-automated and fully automated work.

9164-101, Session PWed

Laser tweezers for determining liquid crystal properties under the influence of external stimuli

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The dynamic response characteristics of a liquid crystal (LC) device are dependent upon its viscosity coefficients and dielectric anisotropy. Optimisation of these properties allows for LC devices with faster response times. With such a wide variety of LC materials, information regarding the viscous properties is often incomplete. The effect of external stimuli, including temperature and electric fields, on these properties provides valuable information for device behaviour. Laser tweezers provide alternate routes to determine this information, as the dimensions are well suited to these techniques.

Manipulation of micron-sized particles with optical tweezers provides a unique method for LC systems to be studied. Dispersed colloidal particles can be trapped and used to probe the fundamental properties of these systems, particularly anisotropic viscosity coefficients in the low Ericksen regime. These properties can be explored under a variety of external conditions, and with different tweezing techniques such as viscous drag measurements or particle tracking.

Optical tweezers also allow the forces acting on colloidal particles in these systems to be explored. The response of trapped particles can provide insight into the behaviour and motion of particles in such systems. The influence of anisotropic LC properties, and of external stimuli, on this behaviour can be studied for a wide variety of materials.

9164-102, Session PWed

Anomalous diffusion of active brownian particles in random potentials

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Brownian particles undergo stochastic and random motion due to the thermal agitation in the surrounding medium. In recent years, a lot of attention has been devoted to the study of active Brownian particles, i.e., microscopic particles capable of self-propelling. These active particles are out-of-thermal equilibrium and, therefore, they explore their environment differently from passive Brownian particles. Recently, the properties of such active particles in complex environments have started to be explored. For example, it has been shown that the interaction of active Brownian particles with a complex environment can be used to develop novel sorting, classification and dialysis techniques based on the swimming style of these particles. In this work, we study experimentally and numerically the motion of Brownian particles in complex potentials and in complex media. The complex potentials are generated by using speckle light fields, while complex media are obtained by adding some bio-propellers (E-coli bacteria) to the solution. We show that both the presence of complex potentials and the presence of complex media have an influence on the motion of the particles. In particular, we demonstrate the gathering and segregation of Brownian particles in the region of interest by speckle light fields and bio-propellers making them suitable for target delivery applications.

9164-103, Session PWed

Simulation of active brownian particles in optical potentials

Giorgio Volpe, Sylvain Gigan, Institut Langevin (France); Giovanni S. Volpe, Bilkent Univ. (Turkey)

Differently from passive Brownian particles, active Brownian particles, also known as microswimmers, are capable of driving themselves out of equilibrium by taking up energy from their environment and converting it into directed motion. Therefore, understanding their motion can provide insight into out-of-equilibrium phenomena associated both to biological entities such as bacteria and to artificial microswimmers. In particular, it is interesting to consider how these active particles can interact with a complex optical potential. Here, we discuss how to mathematically model their motion using a set of stochastic differential equations and how to numerically simulate it by using the corresponding set of finite difference equations both in homogenous and complex environments. In particular, we show how active Brownian particles do not follow the Maxwell-Boltzmann distribution –a clear signature of their out-of-equilibrium nature– and how, differently from passive Brownian particles, microswimmers can be funnelled, trapped and sorted taking advantage of the out-of-equilibrium nature of their motion.

9164-104, Session PWed

Multiplexed spectroscopy with holographic optical tweezers

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We are developing a multiplexed spectroscopy system incorporating holographic optical tweezers with an imaging spectrometer to manipulate optically trapped sensor particles and detect their fluorescence spectra. The system builds on previous work in which we have trapped single pH-sensitive fluorescent microspheres. Sensor particles, which incorporate quantum dots or fluorescent dyes, are capable of measuring local environmental properties including pH, ion concentration, temperature, and voltage by monitoring changes in the fluorescence spectrum. We plan to use these sensors to detect such properties in microfluidic devices and cells.

Our system uses a spatial light modulator (SLM) to control the positions of optical traps so that sensors can be positioned into regions of interest. The fluorescent sensors are excited with a wide field source or by alternating the SLM control between the trapping laser and the excitation laser to excite individual sensors locally. Use of a 532 nm excitation laser with a 1064 nm trapping laser opens a wide spectral window to study fluorescence. The spectra of multiple sensors are detected simultaneously in our system with the use of an imaging spectrometer. We obtain accurate measurements of changes in the fluorescence spectra by calibrating the spectra to the locations of the sensors when the zeroth-order image is viewed through the spectrometer on the CCD. The spectrometer slit must remain open to view sensors distributed across a sample; therefore, the spectral resolution is limited by the size of the particles. Results will be presented to display the capabilities of our system.

9164-105, Session PWed

Numeric modeling approximation of the fluid dynamics in an optical fiber trap

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This document presents a first approach to study the behavior of a static fluid radiated by infrared light (980 nm, 100 mW) transmited by a single-mode optical fiber, for this simulation temperature and radiation pressure are calculated based on the Intensity delivered by a laser diode. The Computing Fluid Dynamics (CFD) results were base on a mesh Tet/Hybrid, TGrid for a Silica micro-particle and a mesh Hex/Wedge, Cooper for the beam. The results show that as the particle moves along the axis, temperature and pressure decreases, having the points of mayor temperature and pressure around the axis. The conclusion of this work

is that it is possible to simulate the interactions between the beam, the micro-particle and the surrounded medium in terms of temperature and pressure using the energy and viscous model.

9164-106, Session PWed

Holographic generation of vector beams with upper-bound diffraction efficiency

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Vector beams (VB) have attracted significant interest due to its unique characteristics. In particular, the presence of a strong longitudinal component of the electric field and tighter focusing in comparison to homogeneously polarized beams. Several generation methods for obtaining VB have been reported, however, most of them are unstable, complicated and/or the output efficiency is small. One promising method of generation of vector beams is synthetic phase holograms (SPH) due to its versatility and flexibility. We recently demonstrated that when the SPH called kinoform is used to encode an arbitrary nondiffractive optical field, its Fourier the spectra and its corresponding noise do not overlap. Consequently, the desired nondiffractive optical field is generated with upper bound-diffraction efficiency and high quality of reconstruction (Mendez, G.; Fernandez-Vazquez, A.; Generation of an arbitrary nondiffractive optical field with upper bound diffraction efficiency: Theory and experimental generation of Parabolic fields; Optics Communications vol. 309 November 15, 2013. p.p. 175-179). In this work we present numerical and experimental generation of reconfigurable vector beams employing SPH that provide the optimum diffraction efficiency and high quality of reconstruction. The vector beams with spatially variable polarization are generated by the linear recombination of two orthogonally homogeneous polarized scalar modes. The scalar modes are generated with a SPH displayed in a phase-only Spatial Light Modulator (SLM) and superimposed using a common-path interferometer which consists of a 4-f system. We demonstrate the generation of high order TE and TM vector Bessel, Mathieu and Weber beams which could be used for optical trapping applications.

9164-107, Session PWed

Studying biofuel aerosol evaporation rates with single particle manipulation

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The significant increase in the greenhouse effect, air pollution, and the impact on climate change due to the burning of fossil fuel has led to the research of alternative energies. Bio-ethanol, obtained from a variety of feedstocks can provide a feasible solution [1]. Mixing bio-Ethanol with gasoline leads to a reduction in CO emission and in NOx emissions compared with the use of gasoline alone [2]. However, adding ethanol leads to a change in the fuel evaporation [3]. Here we present a preliminary investigation of evaporation times of single ethanol-gasoline droplets. In particular, we investigated the different evaporation rate of the droplets depending on the variation in the percentage of ethanol inside them. Two different techniques have been used to trap the droplets. One makes use of an electrodynamic balance (EDB), the other a 532nm optical tweezers set up. The mean size of the droplets trapped by the use of the first technique was ~25 microns, while of those trapped by the use of the second one was ~13 microns. The droplets decreasing size was measured using elastic light scattering and video analysis respectively. In both cases measurements were conducted at 7oC and a controlled environment has been preserved by flowing nitrogen into the chamber. Binary phase droplets with a higher percentage of ethanol resulted in longer droplet lifetimes (0.2s for pure gasoline, 0.4s for 30% of ethanol, 0.8s for 70% of ethanol). Our work also highlights advantages and disadvantages of each technique for such studies. In particular it is challenging to trap droplets with low ethanol content (such as pure gasoline) by the use of EDB. Conversely such droplets are trivial to trap using optical tweezers. We also present data outlining the difficulties in trapping such aerosols in different temperature regimes, and how fuller data sets can be acquired by using both types of instruments.

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9164-109, Session PWed

Optical nanofiber integrated into an optical tweezers for particle manipulation and in-situ fiber probing

Ivan Gusachenko, Okinawa Institute of Science and Technology (Japan); Mary Frawley, Univ. College Cork (Ireland); Viet Giang Truong, Síle G. Nic Chormaic, Okinawa Institute of Science and Technology (Japan)

We present an integrated platform for particle manipulation consisting of a combined optical nanofiber and optical tweezers system. Individual silica microspheres are introduced to the nanofiber at arbitrary points using the optical tweezers, thereby producing pronounced dips in the fiber transmission. We show that such consistent and reversible transmission modulations depend on both particle and fiber diameter, and may be used as a reference point for in-situ nanofiber or particle size calibration. Particles can be prepared in various arrangements prior to releasing from the optical tweezers onto the nanofiber, and are propelled along the fiber length; upon propulsion, they self-arrange into structured arrays, induced by inter-particle optical forces. Integration with an optical tweezers is promising for detailed studies of the optical binding, which is a fundamental phenomenon observed in many optical systems. We also demonstrate a 'particle jet' created by a strong optical trap in optical tweezers, and use it to feed a supply of microspheres to the nanofiber surface, forming a particle conveyor belt. Combining those two trapping devices can be promising for high throughput cytometry or particle sorting and recognition. In conclusion, the demonstrated integrated optical platform provides a method for selective evanescent field manipulation of micron-sized particles, including cell sorting, and facilitates studies of optical binding and light-particle interaction dynamics.

9164-110, Session PWed

Towards polarization-sensitive trapping of metal nanoparticles in double nanohole apertures

Ivan Gusachenko, Viet Giang Truong, Síle G. Nic Chormaic, Okinawa Institute of Science and Technology (Japan)

Double nanohole apertures in metal films have proven to be efficient plasmonic devices for trapping nanoparticles as small as single proteins [Y. Pang, R. Gordon, Nano Letters, 12, 2012]. Moreover, other contrasts such as fluorescence spectroscopy and Raman scattering

can be implemented on those systems. We exploit similar structures to optically trap fluorescent nanoparticles, and are developing a system for fluorescent lifetime and correlation spectroscopy of trapped objects using TCSPC hardware. A combination of time-resolved spectroscopies with single molecule trapping can be promising for studying single molecule interactions via FRET or fluorescence quenching observations. Not only does time resolution add substantially new information about the sample behaviour, but also it allows for increasing SNR because contamination from the excitation light can be temporally filtered. We propose the application of this system for studying the interaction of flagellar motor complex proteins in bacterium Salmonella.

9164-111, Session PWed

Multi scale manipulation of microbubbles employing simultaneous optical and acoustical trapping

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Micrometer-sized gas-filled bubbles, primarily used for improving ultrasound imaging contrast, are finding ever wider use in the field of medicine. As these fields grow, so do the safety implications for the bubbles' manufacture. This drives the need for experimental facilities capable of manipulating the position of bubbles over long ranges (>1000x bubble radii) and with fine resolution (<1x bubble radii) to allow for the directing of bubbles into the path of instruments capable of probing the bubbles' mechanical properties. We present a dual-modality microbubble trapping system that incorporates the fine spatial resolution of optical tweezers, operating in a Laguerre-Gaussian (LG) mode, with the long range, high force manipulation of an acoustic tweezer, in a single microfluidic system. Through back focal plane interferometry we characterise the tweezers in terms of the spring constant and measure the forces involved, including acoustic pressures in the liquid. The response of the trapped microbubbles is observed during the control of the optical trap diameter (LG mode), acoustic frequency and power supplied to each trap. We note the differences between the effect of these parameters on high refractive index particles and low refractive index microbubbles. Further development of the system to include acoustic emission measurement is presented, with the goal of having a multi-purpose mechanical and cavitation detection set-up combined into a single system.

9164-112, Session PWed

Micro- and nano-particle trapping using fibered optical nano-tweezers

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Micro- and nano-particles were trapped in aqueous suspension using our fiber-based optical tweezers. Compared to conventional experiments, our main motivation is to understand the involved forces, and to use this as a tool for the manipulation of small nanoparticles that can hardly be trapped under usual conditions.

For 1µm commercial polystyrene particles, transient trapping was obtained with a single fiber nano-tip, whereas stable trapping over hours was realized with two fiber tips facing each other. The particle position was controlled by modifying the relative light intensities in the two fiber tips. Using Boltzmann statistics of the particle position fluctuations the trap potential was found to be harmonic, both in transverse (perpendicular to fiber axis) and longitudinal directions. The maximal trap stiffness was estimated to 1fN/nm for a tip-to-tip distance of 6µm and 6mW light intensity in each fiber tip. This value was confirmed applying Einstein–Ornstein–Uhlenbeck and autocorrelation approaches.

Nanoparticle trapping was studied using luminescent Ce:YAG particles to allow for direct optical observation. A specific glycothermal synthesis route was successfully developed to elaborate 300nm sized spherical particles with high colloidal stability in water (ζ-potential=43mV). In this case stable trapping with stiffness of 0.3fN/nm was observed for a tip-to-tip distance of 9µm and 8mW. The trapping potential was harmonic in the transverse direction. In the longitudinal direction three minima at about half the wavelength distances were observed.

Finally, using a 3D-finite-elements method (Comsol), some simulations of these configurations have been performed to be compared with experimental results.

9164-113, Session PWed

Object-adapted trapping and shape-tracking to probe a bacterial protein chain motor

Matthias Koch, Julian Roth, Albert-Ludwigs-Univ Freiburg (Germany); Alexander Rohrbach, Albert-Ludwigs-Univ. Freiburg (Germany)

The locomotion of swimming bacteria is normally related to rotary motors as e.g. flagella motors. This study concentrates on the helical bacterium Spiroplasma melliferum, a plant and arthropod pathogen which lacks a stiff cell wall in contrast to most other bacteria. It is able to deform itself intensively, a property that is used for propulsion by generating a pair of kinks propagating down the length of the cell body - thus representing a linear motor. Kinks are generated by a cytoskeletal ribbon made of the unique protein Fibril, whose subunits can change their length through conformational changes. However, the functional principle and the mechanics of the Fibril ribbon have not yet been completely understood.

We use the recently developed object-adapted optical trapping and shape-tracking technique [1] to image the shape deformations of the only 200nm thin cell body while it is hold by an optical line trap. Based on space-resolved light scattering and interference, we are able to record 3D movies of the trapped, self-propelling cell at nanometer precision and frame rates up to 1 kHz. We then analyze the response of the linear motor complex on different external stimuli such as different poisons and optical forces, which are smoothly distributed along the cell body. These observations can be linked to a physical model of the underlying potential landscape of the motor, describing the switching of individual subunits by Kramer's rate theory. We further test this model by exerting forces via optically trapped beads attached to the cell.

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9164-114, Session PWed

Visco-elastic properties of artificial cytoskeletal networks with optically trapped anchor points

Matthias Koch, Dominic Ruh, Alexander Rohrbach, Albert-Ludwigs-Univ. Freiburg (Germany)

Microtubules are biopolymers which self-organize over a large spatial and temporal scale in living cells as a response to a variety of external stimuli. Most of the highly complex intracellular processes like cell-division or mechanotransduction are based on microtubule networks. However, there is only little knowledge about the role of the meshwork geometry on the transport of mechanical momentum in a two dimensional microtubule network.

We use time-multiplexed optical tweezers to generate an array of anchor points for the microtubule network. Fluorescently labeled microtubules are then attached to and spanned between individually trapped 1µm neutravidin beads. We use one trap as actor to exert varying forces on one bead and resolve the positions of all beads by back focal plane interferometry [1]. Despite acting as anchors, the beads are also used as sensors for the response of the network on the actor, thus resolving momentum propagation. This configuration allows probing the visco-elastic properties of biopolymers in synthesized networks in a bottom-up approach and might reveal deeper insights in their complex interaction as part of the cytoskeleton.

We present a mechanical model and simulations of different network topologies and compare these to experimental results. First basic configurations are presented that can be regarded as elementary network elements.

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9164-115, Session PWed

Holographic optical tweezers: microassembling of shape-complementary 2PP building blocks

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Based on an ongoing trend in miniaturization and due to the increased complexity in MEMS-technology new methods of assembly need to be developed. Recent developments show that particularly optical forces are suitable to meet the requirements. The unique advantages of optical tweezers (OT) are attractive due to their contactless and precise manipulation forces. Spherical as well as non-spherical shaped preforms can already be assembled arbitrarily by using appropriate beam profiles generated by a spatial light modulator (SLM), resulting in a so called holographic optical tweezer (HOT) setup. For the fabrication of shape-complementary preforms, a two-photon-polymerization (2PP) process is implemented. The purpose of the process combination of 2PP and HOT is the development of an optical microprocessing platform for assembling arbitrary building blocks. Here, the optimization of the 2PP and HOT processes is described in order to allow the fabrication and 3D assembling of interlocking components. Results include the analysis of the manufacturing accuracy as well as an optimization of the localization process of 2PP microstructures in the fluid. In conjunction, the related transport and storage processes for complex microcomponents have been realized. Besides, the applied detachable interlocking connections of the 2PP building blocks are visualized by an application example. In the long-term a full optical assembly method without applying any mechanical forces can thus be realized.

9164-116, Session PWed

Microfluidic chip for cell sorting

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We will demonstrate specially constructed microfluidic platform for optical sorting application. The main advantage of the chip system is fabrication by combination of two photon nano-litography technique (TPP) and cryo temperature deep reactive ion etching technique (DRIE) into biocompatible glass type substrates. These techniques give us certain freedom in construction of the chip system and therefore very complicated structures can be created. Microfluidic chip was incorporated into our active optical sorting system based on fast galvano-optics steering of the optical trapping beam. As the decision level for sorting we used specific Raman signal peaks that correspond to vitality of the cells. Efficiency and throughput of the chip for sorting was evaluated for various types living microorganisms.

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9164-117, Session PWed

Force dependence of phagosome trafficking in retinal pigment epithelial cells

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Retinal pigment epithelial (RPE) cells play an integral role in the renewal of photoreceptor disk membranes. As rod cells shed their disk membranes, they are phagocytosed and degraded by the RPE, and a failure in this process can result in retinal degeneration. We have studied the role of myosin VI in phagocytosis in a human RPE primary cell line (ARPE-19), testing the hypothesis that this motor generates the forces required to traffic phagosomes in these cells. Experiments were conducted in the presence of forces through the use of in vivo optical trapping. Our results support a role for myosin VI in phagosome trafficking and demonstrate that applied forces modulate rates of phagosome trafficking.

9164-118, Session PWed

Anomalous behavior of a three-dimensionally optically trapped super-paramagnetic particle

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Superparamagnetic particles are used extensively in diagnostics and other research applications for the purification of cells and biomolecules, etc. Here, we demonstrate full 3D optical manipulation of such sub-micrometer sized particle using optical tweezers. Due to the presence of of absorbing iron oxides in the polymer matrix the particle is heated by the laser light. We discuss properties of the optical trap and particle heating for various laser power in the sample space.

9164-119, Session PWed

Sub-micron optical manipulation through phase tuning of light

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Optical trapping by the evanescent field, as it overcomes diffraction limits of optical tweezers, can be a promising tool for developing lab-on-a chip devices for sorting and analyzing particles at nanoscale. While transporting methods have been studied extensively, methods for positioning and manipulating particle are not as well known. However, developing technique which can control the position of a trapped particle would enable investigation of the fundamental properties of bio particles, as well as integration of the optical analysis with and imaging of particles at nanoscale. Here, we propose and demonstrate a design to precisely control the trapping position of a particle through phase tuning of light. Device is composed of a SU8 waveguide with an intended gap in a PMMA/PDMS fluidic channel. By coupling counter-propagating beams into the SU8 waveguide, a standing wave pattern is generated in the gap to trap a particle. Use of two separate counter-propagating beam allows arbitrary variation of the relative phase and intensity of the two input light into the gap, enabling trapping at, and moving to, of particles at arbitrary positions within the gap. Simulation of E-field distribution in the gap predicts that trapping of 2 um sized particle at with 100 nm accuracy is possible at room temperature. We have achieved trapping of particle at a stationary point using the counter-propagating beams, and will present results of sub-micron control of particle location via phase control.

9164-121, Session PWed

Singular optics in tractor beams

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The recently found optical pulling force achieved by illuminating a nondiffraction beam on dielectric particles can be explained by momentum conservation: when the forward scattering exceeds the backward one, the particle receives the backward recoil momentum. So far this momentum enhancement is explained by interference between dipoles or higher orders and optical pulling force is represented by integrating stress tensor at a black box enclosing the object. Being a basic concept in electrodynamics, the Poynting vector plays a dramatic role in understanding the physics of light scattering and optical force. Meanwhile singular points of Poynting vector can reveal the change of energy flow in the near field. In this proceeding, singular optics of nonparaxial light beams in the near field is investigated when the light behaves as a tractor beam. We showed the distributions of Poynting vector for various radiuses of the sphere under nonparaxial beam and expounded how optical pulling force is achieved in term of singular points. Forward momentum enhancement is interpreted as the transfer of the stored azimuthal Poynting vector to longitudinal component redirected by these singular points. The results can be useful to give a clear physical picture of the light-matter interaction and significance of singular optics in manipulating the optical force.

9164-122, Session PWed

Beam-splitting waveguides induced in nanocolloids

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It has been shown that a spatial soliton can be created when a CW laser travels through a suspension of dielectric nanoparticles, provided its power is above a critical value [Opt. Lett. Vol. 7: 276 (1982)]. Recently, it was demonstrated that these soliton-like beams can be used as waveguides for controlling an additional low-power laser (probe beam) [Opt. Lett. Vol. 38: 5284 (2013)]. Here, we present an experimental study of the interaction between two soliton-like beams propagating through a nanocolloid. Moreover, we analyze the possibility to use these solitons to create a beam splitter for a probe beam.

9164-124, Session PWed

Generation of hollow optical beams for optical manipulation

Alexey P. Porfirev, Samara State Aerospace Univ. (Russian Federation) and Image Processing Systems Institute (Russian Federation); Roman V. Skidanov, Image Processing Systems Institute (Russian Federation) and Samara State Aerospace Univ. (Russian Federation)

We demonstrate a technique for the generation of hollow optical beams (HOB's), the cross-section intensity distribution of which has a predetermined shape. This technique is based on using multimodal Bessel beams. We can generate Bessel-like non-diffracting beams by varying parameters of individual beams and adjusting their individual energy contribution to the generated light distribution. This technique allows designing transmission functions for elements that shape both non-rotating and rotating beams. Designed diffractive optical elements simulated using Fresnel transform. HOB's, the cross-section intensity distribution of which has a predetermined shape were successfully formed by using spatial light modulator. Experimental results agree well with the theoretical analysis. Such laser beams can be used for the controlled manipulation of non-spherical objects in liquids or air (the non-spherical particle is trapped in the dark region on axis).

9164-125, Session PWed

Plasmonic Archimedes spiral for selective optical trapping and rotation of optically isotropic particles

Wei-Yi Tsai, Jer-Shing Huang, Chen-Bin Huang, National Tsing Hua Univ. (Taiwan)

Optical manipulation of very small particles has long been challenging due to reduced gradient force. Rotation of particles by light is even more difficult since that requires the particle to be absorbing or to exhibit large polarizability and optical anisotropy. Recently surface plasmon-enhanced optical near field has been used to effectively trap small particles. However, rotation and spinning of isotropic dielectric and transparent particles by optical near field remain challenging. Here, we report the first experimental demonstration of selective trapping or rotation of isotropic dielectric micro-particles using one single plasmonic device, a plasmonic Archimedes spiral. Depending on the handedness of the input circularly polarized light, we show selective generation of a near field focusing hot spot for particle trapping or a plasmonic near-field vortex for particle rotation. Such functionality is of great interest and may find applications in various fields, such as protein folding analysis and local mixing in microfluidic channels.

9164-126, Session PWed

Trapping and manipulation using Rayleigh convection generated by laser-induced heating of an absorbing thin film

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In previous works [1] large gas bubbles trapped in oil were manipulated by thermocapillary forces due to high absorbing films using a low power semiconductor laser (10 mW at 635nm). More recently, microparticles dissolved in water were manipulated using a metallic substrate but at much higher power (>100 mW at 532 nm) resulting in the creation of vapor bubbles [2]. The convection current modulated by the presence of the vapor bubble leads to trapping and manipulation of microparticles a ring around the beam and bubble center. Here we show that vapor bubbles can be avoided but trapping it is still possible using low power laser (<10 mW). The device consist of a thin film of a:Si (1micron and absorption coefficient of ~5e4 cm-1) deposited on glass substrate. Particles are dissolved in water contained between the a:Si film and a cover glass plate separated by an spacer of 120 microns. Light absorption at the a:Si film generates the convection currents. For low power (~1 mW) particules are trapped in the center of the beam but for higher power (~3 mW) particles form a ring around the beam due to two competing forces: Stokes and thermophoretic forces. We calculated these forces and the speed at which the particles were trapped. Numerical simulations confirm that thermal gradients are responsible for the trapping mechanism.

[1] A. Ohta et al. Appl. Phys. Lett. 91, 074103 (2007).

[2] Y. Zheng,et al. Lab Chip 11(22), 3816–3820 (2011).

9164-127, Session PWed

Various superpositions of Bessel beams for capture and controlled rotation of microobjects

Alexey P. Porfirev, Andrey A. Morozov, Mikhail A. Rykov, Roman V. Skidanov, Image Processing Systems Institute (Russian Federation); Sofia V. Ganchevskaya, Samara State Aerospace Univ. (Russian Federation)

The authors present a technique for modulation laser beams into beams with special properties, capable of trapping and rotating objects of micro-size. There are two approaches covered: the first one utilizes zero-order Bessel beams superposition for light tubes shaping, and the second one forms Bessel beams superpositions with diffractional optical elements with spatially partitioned topological charge or, alternatively, with vortex axicones.

Diffractional optical elements simulated using FFT and are brought to binary form for easy manufacture. Binary form DOE are manufactured as quartz-plate etched reliefs, while multi-level DOE forms are studied using SLM.

The authors also cover micromechanical object manufacturing, optimized for rotating in vortex Bessel beams superposition. Such microobjects are manufactured by photolitography. Results of numerical simulations and experimental data are presented and then discussed.

9164-128, Session PWed

Study of light extraction efficiency of QWIP-LED enhanced by photonic crystal slab based on simulation

Yihe Hou, Dongdong Zhang, Shanghai Institute of Technical Physics (China)

QWIP-LED is a new type of infrared up-converter, which can up-convert mid-infrared(9μm) incident light to near-infrared(870nm) output radiation. QWIP-LED/CCD is capable of mid-infrared imaging detection with remarkable advantage of low cost compared with traditional infrared sensor, such as HgCdTe. Unfortunately, the low light extraction efficiency(≈2%) of QWIP-LED prevent this technology from wide application.

In this paper, we introduce Photonic Crystal Slab (PCS) into QWIP-LED to improve light extraction efficiency specifically to its radiation wavelength of 870nm. First, the possible mechanism beneath light extraction enhancement is introduced. And then the model of QWIP-LED containing PCS structure is built using simulation software EastFDTD. The PCS introduced is basically air hole array in triangular arrangement. The structural parameters (lattice constant a, the ratio of radius to lattice constant r/a, PCS thickness d) of the PCS can be changed in certain ranges. Using FDTD (Finite Difference Time Domain) method we calculate the enhancement of the light extraction efficiency under various PCS parameters, and get a combination of optimized PCS structure parameters under which the efficiency is enhanced 2.32 times. The mechanism underneath the enhancement of the light extraction is analyzed based on PCS band theory and effective medium theory. Based on the analysis, a conclusion was drawn that light extraction efficiency can be enhanced to some extent by single PCS structure, but other measures are needed for further enhancement.

9164-80, Session 16

Photonic clusters: potential energy surfaces and reaction pathways for optical assembly of nanoparticles

Zijie Yan, The Univ. of Chicago (United States); Stephen K. Gray, Argonne National Lab. (United States); Norbert F. Scherer, The Univ. of Chicago (United States)

Potential energy surfaces and the associated reaction paths they define have played an important role in understanding the assembly of molecules. Here we show that similar mechanistic effects exist in light-driven self-organization of metal nanoparticles; by analogy, atoms are replaced by silver nanoparticles and optical trapping/optical binding interactions serve as “covalent bonds”. Structurally stable 2D and 3D clusters with various geometries were photonically synthesized with nanometer scale precision in their inter-particle separations using simple Gaussian optical fields. We demonstrate that the formation of specific clusters is ‘path-dependent’, i.e., the assembly depends on the initial positions and hence paths the nanoparticles take upon entering the optical field. The equilibrium geometries and pathways for assembly measured in experiment agree with what is expected from electrodynamic simulations and, in particular, the electrodynamic potential energy surface constructed from these simulations. This work paves the way for rational design of photonic clusters in optical fields with appropriate optical beam shapes and gradients.

9164-81, Session 16

Optical binding between nanoparticles of complex shape

Simon Hanna, Stephen H. Simpson, Univ. of Bristol (United Kingdom)

The optical binding forces between clusters of non-spherical particles of varying symmetry are examined using a computational model. Previous studies have focussed on binding of spheres and nanowires. Here we examine the interactions occurring between particles of varying symmetry in counter-propagating plane waves. We examine, in particular, the 2-dimensional optically-induced self-assembly of particles with 2-fold, 3-fold and 4-fold rotational symmetry, demonstrating the formation of stable ordered clusters. The optical binding calculations are incorporated into Brownian dynamics simulations, including hydrodynamic interactions, enabling the thermal stability of these clusters to be studied. The introduction of structural heterogeneities, in the form, for example, of Janus particles, allows dynamically disordered structures to be examined. Comparisons are drawn with recent experimental results.

9164-82, Session 16

Waveguides in colloidal nanosuspensions

Karen P. Volke-Sepúlveda, Luis A. López-Peña, Yadira Salazar-Romero, Univ. Nacional Autónoma de México (Mexico); Roland A. Terborg, Institute of Photonic Sciences (Spain); Juan Hernández-Cordero, Univ Nacional Autónoma de México (Mexico); Juan P. Torres, ICFO - Institut de Ciències Fotòniques (Spain)

We present and discuss a set of experiments based on the application of the nonlinear properties of colloidal nanosuspensions to induce waveguides with a high-power CW laser beam (532nm) and its use for controlling an additional probe beam. The probe is a CW laser of a different wavelength, whose power is well below the critical value to induce nonlinear effects in the colloidal medium. We also discuss a diagnosis technique for the characterization of the induced waveguides and their performance.

9164-83, Session 17

Formation and manipulation of L-phenylalanine crystal by a laser beam focused at a solution surface

Ken-ichi Yuyama, National Chiao Tung Univ. (Taiwan); Teruki Sugiyama, Instrument Technology Research Ctr. (Taiwan); Hiroshi Masuhara, National Chiao Tung Univ. (Taiwan)

Laser trapping of molecular clusters due to radiation pressure of a focused laser beam has attracted much attention as a high potential method for spatial-temporally controllable crystallization. In the past several years, we have successfully demonstrated glycine and L-alanine crystallization by trapping their liquid-like clusters at a surface of the D2O solution. In this paper, we report on the formation and manipulation of single L-phenylalanine crystal by laser trapping at a surface of the unsaturated H2O solution. When a continuous-wave laser beam of 1064 nm was focused at the surface through an objective lens (60 magnification, NA = 0.9), the single anhydrous crystal was formed from the focal spot. The further irradiation directly into the crystal led to continuous crystal growth on the solution surface, giving thin plate-like crystal. During its growth, the growth rate could be also controlled arbitrarily by changing the power, which indicates that the amount of L-phenylalanine molecules/clusters trapped and adsorbed at the crystal edge is controllable with laser trapping. It was also possible to stop the growth completely and dissolve the crystal by optimizing the power. Moreover, the crystal trapped at the focal spot could be spatially manipulated on the solution surface. During the manipulation, changing polarization of the trapping laser could control the direction of the crystal. These spatial-temporally controlled nucleation, size control, and crystal manipulation will be one of new application techniques of laser trapping.

9164-84, Session 17

Manipulation of particles by laser tweezers-induced gradient of order in the nematic liquid crystal

Igor Musevic, Jožef Stefan Institute (Slovenia); Miha Skarabot, Univ. of Ljubljana (Slovenia); Natan Osterman, Ziga Lokar, Jožef Stefan Institute (Slovenia)

We demonstrate manipulation and transport of microparticles and molecules by the thermally induced gradient of the order parameter in the nematic liquid crystal. We use IR light absorption of the laser tweezers to heat locally a thin layer of the nematic liquid crystal by several degrees. This creates a spatial gradient of temperature of the nematic liquid crystal over tens of micrometers, which not only generates force on the particles, but also induces flow of the liquid crystal. We show that colloidal particles are attracted into the hot spot of the tweezers. The depth of the trapping potential scales linearly with particle radius, indicating that the trapping mechanism is due to elastic self-energy of the distorted nematic liquid crystal around the particle and softening of the elasticity with increased temperature of the liquid crystal. We also demonstrate that this thermal trapping mechanism is efficient down to the nanoscale, as fluorescent molecules are also transported into hotter regions of the liquid crystal. This effect is absent in the isotropic phase, which calls into question particle transport due to the Soret effect. The flow is governed by the dynamic thermal expansion in a gradient of viscosity, local decrease and melting of the nematic order.

9164-85, Session 17

The break-up dynamics of liquid threads revealed by laser radiation pressure and optocapillarity

Jean-Pierre Delville, Univ. Bordeaux 1 (France); Julien Petit, Technische Univ. Darmstadt (Germany); Matthieu Robert de Saint Vincent, Univ. de Rennes 1 (France); David Rivière, Hamid Kellay, Univ. Bordeaux 1 (France)

We show how optofluidics (radiation pressure or optocapillary stresses) in two-phase liquids opens the way for investigating the difficult problem of liquid thread breakup at very small scales when the roughness of the surface becomes important or when surfactant are present at the interface. The production of monodisperse droplets is indeed desirable, and the exact breakup mechanism needs to be clarified as it determines the size and polydispersity of the drops. The first case happens with nanojets or when nanowires fragment during thermal annealing. Considering near critical interface, where the roughness of the interfaces may be tuned, we use the radiation pressure of a laser wave to produce fluctuating liquid columns and study their breakup. We show how classical visco-capillary breakup, usually governed by a balance between viscosity and surface tension, crosses over to a fluctuation dominated regime. We fully describe this new regime, demonstrate its universality and characterize the transition. On the other hand, using thermocapillary stresses driven by light to actuate the breakup of liquid thread and produce droplet of surfactant laden liquids, we observe deviations from the expected visco-capillary law. We suggest that these deviations are due to the presence of a time varying interfacial tension at the minimum neck location. We extract this quantity from a simple ansatz which incorporates the temporal change of the interfacial tension and allows understanding the dynamics of thinning. These experiments suggests that opto-hydrodynamics becomes a new route to reveal new physics of fluids.

9164-86, Session 18

Dynamic motion of semicircular optical wings

Alexandra B. Artusio-Glimpse, Daniel G. Schuster, Mario W. Gomes, Grover A. Swartzlander Jr., Rochester Institute of Technology (United States)

Conventional work in optical micromanipulation utilizes carefully sculpted laser beams for optical trapping affording unprecedented control of the microscopic world; however, the extent of applications is far from exhausted. Fashioning an object to be forced by uniform light is gaining enthusiasm as the dynamics of these objects while in flight is realized. Working as devices that measure small scale surface characteristics or as space flying microscopic satellites, cambered refracting particles (or optical wings) present a potential for a wide range of applications. This work defines the dynamics of particles with semicircular cross-sections. A simple theory is developed and supported by numerical simulation and preliminary experimentation. Two specific shapes are analyzed while uniformly illuminated - 1) a semicylinder rocking curved side down on a flat surface when gravitational effects persist and 2) a hemisphere floating in gravity-free space. Both of these semicircular optical wings are mirrored on the flat surface. The semicylinder is found to behave as a parametrically driven nonlinear harmonic oscillator such that radiation pressure changes the frequency of rocking oscillation. What is more, we find that above a critical intensity the equilibrium orientation of the wing bifurcates so that the wing stably oscillates about some raised orientation. Solutions to the equation of motion are given for both constant and time varying illumination conditions. In addition, we analyze the hemisphere as it spins about its symmetry axis. Due to the radiation pressure induced torque, the spinning hemisphere will precess in an intensity dependent manner.

9164-87, Session 18

Optical field interactions with non-spherical optical particles

David M. Carberry, Vincent L. Y. Loke, Daryl C. Preece, Timo A. Nieminen, Halina H. Rubinsztein-Dunlop, The Univ. of Queensland (Australia)

Non-spherical optical probes generated via two-photon photopolymerisation have several advantages over traditional microspheres. For example: their interactions with the optical field can be optimised to a desired function, the contact area with specimens can be minimised, and they be designed to operate over multiple force ranges. Here we present our latest results showing how non-spherical optical probes interact with optical fields, and how the added complexity of the probe is more than offset by increases in functionality.

9164-88, Session 18

Optical tweezers as manufacturing and characterization tool in microfluidics

Jannis Köhler, Reza Ghadiri, Sarah Isabelle Ksouri, Evgeny L. Gurevich, Andreas Ostendorf, Ruhr-Univ. Bochum (Germany)

Pumping and mixing of small volumes of liquid samples are basic processes in microfluidic applications. Among the number of different principles for active transportation of the fluids, microrotors have been investigated from the beginning. The main challenge in microrotors, however, has been the driving principle. In this work a new approach for a very simple magnetic driving principle has been realized. More precisely, we take advantage of optical grippers to fabricate various microrotors and introduce an optical force method to characterize the fluid flow generated by rotating the structures through magnetic actuation. The microrotors are built of silica and magnetic microspheres, which are initially coated with Streptavidin or Biotin molecules. Holographic optical tweezers (HOT) are used to trap, position, and assemble the microspheres with the chemical interaction of the biomolecules leading to a stable contact. Using this technique, complex designs of microrotors can be realized. The magnetic response of the magnetic microspheres enables the rotation and control of the structures through an external magnetic field. The generated fluid flow around the microrotor is measured optically by inserting a probe particle next to the rotor. While the probe particle is trapped by optical forces, the flow force leads to a displacement of the particle from the trapping position. This displacement is directly related to the flow velocity and can be measured and calibrated. Variations of the microrotor design and rotating speed lead to characteristic flow fields. Using this method, the fabrication of a microrotor with adjustable size and flow properties can be realized. With the implementation into a microfluidic system it can be used correspondingly as a micropump or for mixing applications.

9164-91, Session 19

Dmitri Petrov: optical tweezers, Raman spectroscopy, and statistical physics *(Invited Paper)*

Giovanni S. Volpe, Bilkent Univ. (Turkey)

No Abstract Available

9164-93, Session 20

Measurements of motor-driven viral DNA packaging with optical tweezers: Evidence that the packaged DNA indirectly modulates motor function

Douglas E. Smith, Zachary Berndsen, Nicholas A. Keller, Damian J. delToro, Univ. of California, San Diego (United States)

e use force-measuring optical tweezers to directly measure the motor-driven packaging of single DNA molecules into single bacteriophage phi29 virus capsids. We have previously shown that the packaging rate slows with increasing capsid filling, suggesting that large forces build up resisting DNA confinement. Here we present preliminary evidence suggesting that packaging is also slowed by an indirect interaction between the packaged DNA and the motor propagated though the portal complex. In addition, of potential technical interest to researchers using optical tweezers, we describe an improved method for accurate calibration of force and displacement measurements using DNA molecules as metrology standards.

9164-123, Session 20

Optical trapping of isolated mammalian chromosomes

Nima Khatibzadeh, Beckman Laser Institute and Medical Clinic (United States); Ann A. M. Bui, Alex B. Stilgoe, The Univ. of Queensland (Australia); Yesenia Rocha, Gladys Cruz, Beckman Laser Institute and Medical Clinic (United States); Timo A. Nieminen, Halina H. Rubinsztein-Dunlop, The Univ. of Queensland (Australia); Michael W. Berns, Beckman Laser Institute and Medical Clinic (United States)

We have investigated optical trapping of isolated mammalian chromosomes, and based on these measurements, we have estimated the forces exerted on them during cell division. A continuous wave ytterbium fiber laser at 1064 nm was used to create an optical trapping system to perform chromosome manipulation experiments. Briefly, the optical system consisted of an inverted Zeiss Axiovert-135 microscope with a 100X/1.4 oil immersion objective through which the laser beam converged to form the optical trap. The laser beam was collimated, steered, and coupled to the microscope through the epifluorescence port. The laser power at the trap focal spot was determined by measuring the input power at the back aperture of the objective lens multiplied by the objective transmission factor at 1064 nm of ≈25%.

Individual isolated chromosomes with mean±s.d. diameter values of ≈0.95±0.16 μm, length of ≈6.71±1.74 μm, and aspect ratio (length/radius) of ≈14.42±3.89 were suspended in liquid media with 1 and 3 cP viscosity prior to trapping. Individual chromosomes were trapped at different trapping powers in the range of ≈20-55 mW. Fluidic viscous drag forces where applied by driving a computer controlled motorized microscope stage at known velocities. Based on the Stokes' equation for flow around cylindrical objects, the drag forces were calculated at the velocities at which the chromosomes escaped from the trap. The preliminary data show a linear relationship between chromosome trapping force and power within the range of the power and suspension media viscosity values used in this study. Our study includes calculation of the dimensionless trap efficiency coefficient (QEscape) at 1064 nm and the corresponding effects of media viscosity and trapping power on that value. The results of this study validate optical tweezers as a non-invasive and precise technique to determine intracellular forces in general, and specifically, the spindle forces exerted on the chromosomes during cell division.

Sunday - Wednesday 17–20 August 2014

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9165-1, Session 1

Ultrafast and two-dimensional electronic spectroscopy of singlet exciton fission in nanoparticle dispersions of functionalized pentacene derivatives *(Invited Paper)*

Ryan D. Pensack, Andrew J. Tilley, Tia S. Lee, Dong Gao, Univ. of Toronto (Canada); Marcia M. Payne, John E. Anthony, Univ. of Kentucky (United States); Dwight S. Seferos, Gregory D. Scholes, Univ. of Toronto (Canada)

Singlet exciton fission has the potential to become a new paradigm in organic photovoltaic devices. While efficient singlet fission has been observed in a number of molecular systems, details regarding the mechanism are only beginning to emerge. Here, we apply pump–probe and two-dimensional electronic spectroscopy to elucidate the mechanism of singlet fission in nanoparticle dispersions of functionalized pentacene derivatives. We find that the nanoparticle absorption spectrum does not vastly differ from that of the constituent molecules suggesting the molecules are weakly electronically coupled and the nanoparticles are disordered. Regardless of this apparent lack of electronic coupling and structural order, we observe the rapid evolution of singlet to triplet transient signatures in the pump–probe spectra on the ultrafast timescale. The formation of triplets is consistent with marked fluorescence quenching that occurs upon nanoparticle formation. Taken together, these observations implicate singlet fission as the mechanism of triplet formation and suggest the efficient conversion of singlet to triplet populations. We have performed pump–probe anisotropy and two-dimensional electronic spectroscopy experiments to understand more clearly the nature of triplet formation in the nanoparticles. In particular, the aim is to differentiate between other physical phenomena that may complicate interpretation of time constants obtained directly from the transient measurements in terms of the intrinsic rate of singlet fission. We also intend to discuss the observation of vibrational coherences in two-dimensional electronic spectroscopy experiments and how monitoring their time evolution may serve to provide additional insight into the mechanism of singlet fission in disordered systems.

9165-2, Session 1

How molecular packing affects the rate of singlet exciton fission

Christopher J. Bardeen, Univ. of California, Riverside (United States); Katharina Broch, Eberhard Karls Univ. Tübingen (Germany); Valerie Nichols, Geoffrey Piland, Univ. of California, Riverside (United States); Frank Schreiber, Eberhard Karls Univ. Tübingen (Germany)

Singlet exciton fission is a spin-allowed process in which a singlet excited state spontaneously splits into a pair of triplet excitons. This process may provide an avenue to higher efficiency solar cells by making it possible to generate two electron-hole pairs per absorbed photon. But a predictive understanding of how molecular-level packing affects the rate of fission has been elusive. In order to clarify the role of intermolecular interactions in this process, we have studied how the rate of singlet fission depends on molecular arrangement in well-defined crystalline systems. In diphenylhexatriene, we compare the fission rates of two different crystal polymorphs, monoclinic and orthorhombic. We find the rate of fission is 50% greater in the monoclinic form, most likely due to the decreased intermolecular separation and better spatial overlap of the molecules in this crystal form.[1] Pentacene has only one polymorph, but the average separation between pentacene molecules can be varied by dilution with an inert molecule, in this case diindenoperylene, while maintaining the overall crystal packing motif. We find that the fission rate and possibly its mechanism both change as the pentacene separation increases. In both molecular systems, the fission rate changes but remains competitive with other relaxation processes. Our results suggest that singlet exciton fission is reasonably robust with respect to molecular packing arrangements.

[1] "Different Rates of Singlet Fission in Monoclinic Versus Orthorhombic Crystal Forms of Diphenylhexatriene," R. J. Dillon, G. B. Piland and C. J. Bardeen, J. Am. Chem. Soc., 135, 17278–17281 (2013).

9165-3, Session 1

Singlet fission in organic thin films of 1,3-diphenylisobenzofuran and cibalackrot

Joseph Ryerson, National Renewable Energy Lab. (United States) and Univ. of Colorado at Boulder (United States); Joel N. Schrauben, National Renewable Energy Lab. (United States); Arthur J. Nozik, National Renewable Energy Lab. (United States) and Univ. of Colorado at Boulder (United States); Josef Michl, Univ. of Colorado at Boulder (United States); Justin C. Johnson, National Renewable Energy Lab. (United States)

Efficient singlet fission, which is the generation of two triplet excitons from one absorbed photon in molecular systems, has been observed in polycrystalline thin films of 1,3-diphenylisobenzofuran (1). Solution grown single crystals of two conformational polymorphs of 1 have been characterized by x-ray diffraction (XRD) for full structure determination and fluorescence spectroscopy. Thin films of 1 were prepared by thermal evaporation and solution dropcasting and were characterized by powder XRD, steady-state absorption, steady-state fluorescence, time-resolved fluorescence, and ultrafast transient absorption spectroscopy. Two polymorphs exist in the bulk and in thin films, labeled α and β here. Although the films are likely a mix of α and β crystallites, predominantly α-type films generate 2.0 triplets per absorbed photon at 77 K and 1.4 triplets per absorbed photon at room temperature, whereas β-type films have much lower triplet quantum yields. Fitting of UV-vis absorption spectra corrected for reflection and scattering revealed a 600 cm-1 redshift of the absorption onset of β-type with respect to α-type films. The β-type singlet vibronic state lies too low in energy to access the coupled triplet state necessary for the system to undergo singlet exciton fission. Enhanced stabilization of a rapidly formed excimer state in ?-1 can also account for low efficiency of triplet formation. Cibalackrot (2), a stable indigo derivative which has been shown to exhibit conformational polymorphism, also generates multiple triplet excitons per absorbed photons. Current work focuses on quantifying triplet formation in solution as well as in thin films of 2.

9165-4, Session 2

Towards determining the factors controlling photocurrent generation in low bandgap polymer/fullerene solar cells *(Invited Paper)*

Stoichko D. Dimitrov, Imperial College London (United Kingdom)

The most efficient organic solar cells are now reaching power conversion efficiencies of 10%, but further device improvements are needed for this technology to become commercially viable. A major obstacle to achieve this is our poor understanding of the relationship of charge photogeneration with materials energetics and film morphology.

In this talk, I will present our recent advances in understanding these relationships in polymer:PCBM solar cells. Using femtosecond to millisecond transient absorption spectroscopy, we compared the charge photogeneration dynamics in indacenodithiophene and diketopyrrolopyrrole copolymer: PCBM blends with differing energy

offsets and film morphologies. For the blend with the low energy offset, we observed ultrafast formation of bound-polaron-pair states that geminately recombine to the polymer triplets on a sub-nanosecond timescale. For the higher energy offset blends, device photocurrent was not limited by such geminate recombination, but instead by non-geminate recombination losses. Our analysis of charge photogeneration as a function of film composition revealed that the yield of charges on the picosecond and microsecond timescales correlate with the device photocurrent densities measured under different applied bias.

In addition to charge generation from polymer excitons, we investigated the kinetics of fullerene excitons in diketopyrrolopyrrole:PC70BM blends. Our femtosecond transient absorption spectroscopy results demonstrated that PC70BM excitons can contribute strongly to device photocurrent but are often limited by exciton diffusion to the polymer-fullerene interface. By fractionating the diketopyrrolopyrrole copolymers, we optimised the morphology of the active layer to reduce PC70BM exciton diffusion losses and thus achieved ~7 mA/cm2 photocurrent from PC70BM excitons.

9165-5, Session 2

The roles of bulk and interfacial molecular orientations in determining the performance of organic bilayer solar cells

Guy O. Ngongang Ndjawa, King Abdullah Univ. of Science and Technology (Saudi Arabia); Kenneth R. Graham, King Abdullah Univ. of Science and Technology (Saudi Arabia) and Stanford Univ. (United States); Sarah Conron, Patrick Erwin, The Univ. of Southern California (United States); Ruipeng Li, King Abdullah Univ. of Science and Technology (Saudi Arabia); Kang Wei Chou, Lawrence Berkeley National Lab. (United States); George Burkhard, Stanford Univ. (United States); Lethy Krishnan Jagadamma, King Abdullah Univ. of Science and Technology (Saudi Arabia); Eric T. Hoke, Michael D. McGehee, Stanford Univ. (United States); Mark E. Thompson, The Univ. of Southern California (United States); Aram Amassian, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Molecular orientation has been shown both experimentally and theoretically to play a significant role in determining the performance of small molecule solar cells. In these cells processes such as light absorption, exciton transport, and exciton dissociation are strongly dependent on how the molecules are oriented both in the bulk and at the donor-acceptor interface. While the influence of molecular packing and molecular orientation on the device performance has long been investigated, it remains experimentally challenging to isolate contributions arising from the bulk molecular orientations vs. those from interfacial orientations. This difficulty in part is due to complexities such as molecular rearrangements at the donor-acceptor interface, interaction induced disorder, and intermixing. In this work we use ZnPc/C60 bilayer systems whereby the orientation of the ZnPc molecules is altered by using a thin copper iodide layer to achieve a predominantly face on (on CuI) vs. edge on (on ITO) packing configuration. To independently alter the bulk and interfacial molecular orientation, we conduct very low temperature deposition during the deposition of the donor and/or the acceptor to suppress ordering in the bulk and/or interdiffusion at the interface. These experiments allow us to probe the contributions of the bulk ZnPc layer and the ZnPc/C60 interface by comparing device pairs in which only the bulk or the interface differ. We find that by controlling the orientation in the bulk the short circuit current can be strongly modulated, whereas controlling the interfacial molecular orientation and degree of intermixing mediate the open circuit voltage of the devices.

9165-6, Session 2

Consequence of thermal annealing on PCDTBT-based solar cells performance and composition profile

Olesia Synooka, Kai-Rudi Eberhardt, Chetan R. Singh, Gernot Ecke, Technische Univ. Ilmenau (Germany); Bernhard Ecker, Elizabeth von Hauff, Albert-Ludwigs-Univ. Freiburg (Germany); Gerhard Gobsch, Harald Hoppe, Technische Univ. Ilmenau (Germany)

As reported earlier, the photovoltaic performance of PCDTBT:PCBM polymer solar cells drastically decreases upon thermal annealing. It was demonstrated in the literature, that thermal annealing leads to increased trap formation and as a consequence disturb solar cell performance, especially via a reduced fill factor. This has been demonstrated by space-charge-limited-current analysis and ellipsometry, as well as, structural changes analyse of PCDTBT upon annealing. However, we decided in addition to investigate morphological changes occurring within PCDTBT:PCBM photoactive blend layers upon thermal annealing, as these must have an impact on charge transport. By application of several characterizations techniques, and especially supported by results of Impedance Spectroscopy and Auger Electron Spectroscopy (AES), indeed the existence of an unfavourable compositional gradient within the photoactive layer could be revealed. This compositional gradient may be in part accounted for harming the transport of electrons and holes in either direction.

9165-7, Session 2

Charge separation and recombination dynamics in organic semiconducting photovoltaic systems: role quantum tunneling, delocalization and spin statistics *(Invited Paper)*

Eric R. Bittner, Univ. of Houston (United States)

We present a fully quantum-mechanical model of the electronic dynamics of primary photoexcitations in a polymeric semiconductor heterojunction, which includes both polymer stacking and phonon relaxation. By examining the phonon-induced fluctuations in the state-to-state energy gaps and the exact golden-rule rate constants, we conclude that resonant tunnelling between the primary exciton to delocalized interchain charge-transfer states may be the initial step in the formation of charge-carriers in polymer-based bulk-heterojunction photovoltaic diodes. Using the same theoretical approach, we explore the role of quantum state delocalization in suppressing bimolecular recombination of triplet polarons pairs.

9165-8, Session 3

New insights on the nature of two-dimensional polarons in semiconducting polymers: infrared absorption in poly(3-hexylthiophene) *(Invited Paper)*

Frank C. Spano, Chris M. Pochas, Temple Univ. (United States)

The nature of charges in semiconducting conjugated polymer films has continued to receive a great deal of attention, motivated primarily by the promise of plastic solar cells. In this talk, the IR/NIR absorption spectrum of positive charges (holes) in poly(3-hexylthiophene) - or P3HT -thin films is revisited. P3HT is a semicrystalline polymer which forms ?pi-stacks of cofacially-oriented polymers or polymer segments, separated by intervening layers containing the hexyl side-chains. The existence of

holes delocalized in two dimensions – along the polymer backbone as well as across polymers within a pi-stack, has been associated with the emergence of an IR peak near 0.1 eV due to hole transfer between neighboring chains.[1,2] This talk presents new insights regarding the detailed vibronic structure of the IR band, based on an analysis of a Holstein-style Hamiltonian which includes electronic coupling both along and across chains, vibronic coupling involving the main symmetric ring-stretching mode, and diagonal (site energetic) and off-diagonal disorder. Utilizing the two-particle approximation configurationally-averaged IR spectra are computed which accurately reproduce the vibronic structure observed in the measured spectra. The impact of diagonal and off-diagonal ("paracrystalline") disorder is shown to be polarization sensitive. Short-range disorder along the polymer backbone selectively attenuates the intrachain polaron peaks (P1), while short-range disorder across polymers within a stack selectively attenuates the interchain polaron peak (DP1). The impact of interchain interacitons on polaron coherence is also discussed.

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9165-9, Session 3

Influence of acceptor structure and aggregation on mechanisms of charge generation at organic interfaces

John B. Asbury, The Pennsylvania State Univ. (United States)

We examine the mechanisms of charge photogeneration in archetypal classes of electron acceptors in organic photovoltaics (OPVs) using ultrafast infrared spectroscopy. The molecular structures and crystalline order of acceptors blended with conjugated polymers are found to determine whether hot CT state dissociation can influence the dynamics and yield of photo-generated electrons and holes. Furthermore, the degree of aggregation and therefore charge carrier delocalization within amorphous acceptor phases influences the yield of photogenerated charge carriers. Enhancing the degree of carrier delocalization leads to more efficient charge generation on ultrafast time scales – suggesting that hot CT state dissociation may be most important when OPV materials are able to support extended carrier delocalization. Findings about efficient charge carrier generation in OPV materials that do not contain fullerenes are presented.

9165-10, Session 3

Charge separation in an n-p-n triad forming Lamellar structure

Damien Rolland, Lucia Hartmann, Natalie Banerji, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Martin Brinkmann, Institut Charles Sadron (France); Holger Frauenrath, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Since charge separation in organic photovoltaics takes place between n- and p-type semiconductors, their interface should be maximized within the active layer, while charge percolation pathways to the electrodes should be ensured. One way to obtain an ideal and thermodynamically stable morphology is to covalently link n- and p-type semiconductors, provided a sufficiently high internal order is achieved. To this end, we have synthesized a perylene-quaterthiophene-perylene triad substituted with poly(isobutene) segments that induce order at the nanoscale via microphase segregation. Charge separation under selective illumination on the quaterthiophene or perylene moiety was investigated by steady state and transient absorption spectroscopy, and related to the molecular packing and phase morphology deduced from electron and grazing incidence X-ray diffractions. Photoluminescence was quenched due to charge separation within the triad. In solution, these charges quickly recombined, but were shown to have a longer lifetime in films, which is beneficial for charge collection in photovoltaic devices. We have also investigated whether alignment of the supramolecular aggregates affects the photophysics.

9165-11, Session 3

X-ray photoemission spectroscopy study of vertical phase segregation in polymer: PDI blends

Alberto Brambilla, Alberto Calloni, Politecnico di Milano (Italy); Eduardo Aluicio-Sardui, Istituto Italiano di Tecnologia (Italy); Giulia Berti, Politecnico di Milano (Italy); Zhipeng Kan, Istituto Italiano di Tecnologia (Italy); Serge Beaupré, Mario Leclerc, Univ. Laval (Canada); Hans-Jürgen Butt, Max-Planck-Institut für Polymerforschung (Germany); George Floudas, Univ. of Ioannina (Greece); Panagiotis E. Keivanidis, Istituto Italiano di Tecnologia (Italy); Lamberto Duò, Politecnico di Milano (Italy)

In the context of research on organic photovoltaics (OPVs), the realization of photoactive layers based on bulk heterojunctions (BHJ) of electron donor and acceptor materials forming an interpenetrating network has received significant attention due to their low cost, high efficiency and ease of fabrication. Among most explored materials, poly(3-hexylthiophene) and C61-butyric acid methyl ester (PCBM) blend films have yielded the highest power conversion efficiencies (PCEs) to date, with the drawback of relatively high realization costs. Perylene diimide (PDI) derivatives are a potential candidate for PCBM replacement, being cheaper, showing visible absorption and high electron mobility [1-3]. However, the device performance of PDI-based OPVs is still inferior to that of the PCBM-based cells.

In order to provide a rationale for PDI device improvement, we present here a systematic study on PDI molecules blended with semiconducting polymers, such as (for brevity) F8BT, TFB, PCDTBT and PBDTT-E-O. In particular, we investigated the vertical phase separation in the polymer:PDI blends by means of X-ray photoemission spectroscopy (XPS) and its influence on the PCEs of working devices. According to XPS results, an enhanced segregation of the PDI component at the hole-collecting electrode of PEDOT:PSS is responsible for the low PCE of the 'conventional' OPV devices.

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9165-12, Session 3

What structural features do charge transfer states depend on? *(Invited Paper)*

Natalie Stingelin, Imperial College London (United Kingdom)

We will present a discussion on how microstructural changes affect the electronic landscape of organic solar cells, including charge generation, charge recombination and charge transfer states. We will show, for instance, that the evolution of well-defined interfaces between intermixed and relatively phase-pure domains of the donor and acceptor is required for spatial separation of the electron and hole. This structural characteristic largely controls the yield of free charges. Moreover, we should that the intensity of CT absorption is directly correlated with the presence of a molecularly intermixed donor:acceptor phase and discuss what structural features determine the CT energy.

9165-13, Session 4

Charge recombination in organic and hybrid solar cells: probing buried interfaces *(Invited Paper)*

David S. Ginger, Univ. of Washington (United States)

Control of surface chemistry at buried interfaces has been shown to improve the performance of organic bulk heterojunctions, quantum dot solar cells, and planar heterojunction OPVs. We combine transient photovoltage, transient photocurrent, and scanning probe based surface photovoltage experiments to explore the role of chemical modifiers at the organic/inorganic interface on non-geminate recombination losses in various solution processed solar cells. We show that in selected BHJs chemical modification of the hole extracting contact can increase carrier lifetimes and improve open circuit voltage. Furthermore, we demonstrate the use scanning probe microscopy methods to reveal spatial heterogeneity in carrier lifetimes due to variable surface chemistry at the buried semiconductor/electrode interface.

9165-14, Session 4

Charge separation and energy transfer at inorganic/organic semiconductor interfaces: a case study with ZnO

Francesco Bianchi, Sylke Blumstengel, Stefan Hecht, Fritz Henneberger, Björn Kobin, Norbert Koch, Raphael Schlesinger, Mino Sparenberg, Humboldt-Univ. zu Berlin (Germany)

ZnO is currently attracting significant interest as a candidate for hybrid photovoltaic and light-emitting devices. We studied - in an all-ultrahigh vacuum approach - the interfacing of ZnO with various conjugated organic molecules, including oligo-phenylenes and perylene derivatives, whose fundamental optical excitation is (fully) resonant to the ZnO band gap. The morphology and electronic structure of the hybrid interfaces were determined by in-situ electron diffraction, scanning probe microscopies, photoemission and reflection spectroscopy, complemented by ex-situ transmission electron microscopy and X-ray diffraction analyses. By appropriate interfacial design, we are able to demonstrate (diffusion-limited) electron-hole separation and, alternatively, excitonic energy transfer with efficiencies of up to 80 %.

9165-15, Session 4

Interfacial charge-transfer processes in polymeric organic nitroxy-radical energy storage materials

Madison Martinez, Barbara K. Hughes, Wade A. Braunecker, Ross Larsen, Heather Platt, Thomas Gennett, National Renewable Energy Lab. (United States)

Organic radical batteries (ORBs) comprise a relatively new technology that uses cathodes based on stable polymeric organic radical-based polymers. These materials show great promise as cathodes in batteries because the neutral, radical species (at left, Figure 1) is remarkably stable and the one-electron oxidation depicted is fully reversible. The rate at which charge can be pushed into or extracted from an electrode is determined by the timescales on which charges are able to move within an electrode and across an electrode-electrolyte, electrode-current collector interface. This work focused on various test-cell pressures to determine how the charge/discharge processes based on the radical polymer's redox interfacial and intramolecular mass-transfer processes would be influenced by the external pressure on the organic radical polymer electrode matrix.

With the Redox process shown in Figure 1, the expansion-contraction of the polymer by the inclusion-exclusion of the solvated anions during charge-discharge can have a direct affect on the mass transfer mechanism with the electrode matrix. Therefore, the rate of the interfacial charge transfer may be affected by; nitroxide radical concentration i.e. cathode capacity, pendant group chain length, cathode thickness and the current collector surface.

AC impedance measurement of the composite electrodes at pressure from 25 to 85 inch-lbs revealed a correlation between: the overall electron transfer resistance of the composite electrode and the material of the current collector; capacity of nitroxide polymer; and the charge-discharge rate limits. These data suggest that the ionic conduction pathways both across the solvent-electrode interface and within the electrode matrix can be altered by pressure.

Overall, our results indicate that the interfacial electron transfer processes both within the electrode matrix, and across the electrolyte-electrode interface can dominate the charge/discharge performance of an organic radical battery system. Therefore, the overall performance of these new organic cathode materials could be improved by suitably designing the interfacial structure for specific charge-discharge rate requirements to maximize interfacial charge transfer through distinct composition for maximal pressure, correct polymer expansion and maximized redox sites.

9165-16, Session 4

Photoluminescence investigation of fundamental charge transfer processes in stable nitroxyl radical-containing polymers

Barbara K. Hughes, Andrew J. Ferguson, Wade A. Braunecker, Thomas Gennett, National Renewable Energy Lab. (United States)

The electrochemical redox reactions of stable organic polymer materials with unpaired electrons is a relatively new and exciting area of battery research. Specifically, stable nitroxyl radical-containing polymers have displayed excellent characteristics as the cathode-active material and have presented themselves as low-cost and environmentally friendly alternative to the current Li-ion battery technologies. However, there is a lack of fundamental understanding of the dynamics of charge transfer processes within organic radical-containing polymers.

Since nitroxyl radicals are known fluorescence quenchers, we have investigated photoinduced charge transfer processes between radical polymers and an organic fluorophore. Using extensive photoluminescence studies, we probed charge transport by the incorporation of fluorescent perylene markers into the radical-containing polymer matrix. We have investigated the interplay between collisional and static quenching processes using steady-state and time-resolved photoluminescence quenching studies of perylene by TEMPO (TE2,2,6,6-tetramethylpiperidinyloxyl), radical-containing species. Quenching studies for these model systems, including both free TEMPO monomers and non cross-linked, solution-phase PTMA-nitroxy polymers, (poly(4-methacryloyloxy-2,2,6,6-tetramethylpiperidine-N-oxyl) have allowed us to determine how such polymer properties as average chain length, spacing between pendant groups, proclivity for polymer folding, and solvent swelling affect both the mechanism of quenching as well as the efficiency of charge transfer. As a function of polymer length, we observe a change in quenching mechanism, while the density of radical moieties has significant affects on quenching/charge transfer efficiency. The quenching sphere of action and thus the optimal distance between radical moieties and fluorophores for the most efficient charge transfer has also been determined and will be discussed at length.

9165-17, Session 4

Nano-multilayer V/ZnO transparent conduction thin films

Yu Shan Wei, Yen-Shuo Liu, Cheng-Yi Liu, National Central Univ. (Taiwan)

Nano-multilayer V/ZnO TCLs (transparent conductive layer) were prepared by sandwiching nano V and two ZnO layers by sputtering processes. The total thickness of the V/ZnO nano-multilayer is fixed at 200nm. The electrical properties (resistivity, mobility, carrier concentration) of the V/ZnO nano-multilayer were investigated by Hall measurement. With XPS and HR-TEM analysis on the V/ZnO nano-multilayer, we conclude that the high mobility and carrier concentration of the V/ZnO nano-multilayer attribute to the interface layer forms between the V and ZnO layers: we determine that the Zn and O atoms diffused into immobile V layer and the nano-ZnVxOy layers were formed. Also, we produced several nano-multilayer by splitting V layer into the ZnO layer, which are 1x2, 3x4, 4x5, 6x7, 9x10. The front digit means the layer number of the V metallic layer and the later digit means the layer number of the ZnO layer. The 3x4 structure shows the best electrical conduction among all multi-layer samples. In this talk, we will explain how the nano interfacial layers between V and ZnO contribute the carrier concentration and serve as the carrier mobility path.

9165-18, Session 5

Exciton hopping in carbon nanotube solar cells studied with 2D white-light spectroscopy *(Invited Paper)*

Martin T. Zanni, Univ. of Wisconsin-Madison (United States)

We report a new multidimensional technique, 2D-White-Light Spectroscopy, that is capable of monitoring charge and energy flow over the entire visible and near-IR wavelength range. Using this new technique, we will present data on thin films of semiconducting carbon nanotubes. These thin films are a promising mesoscale architecture for next generation solar cells. We map all possible energy pathways, observe delocalized electronic states, and anti-correlated energy levels. By simultaneously spanning 400 to 1400 nm, 2D-WL provides an unprecedented view of energy flow in carbon nanotubes and other light harvesting materials.

9165-19, Session 5

Direct measurement of energy transport in organic nanosystems *(Invited Paper)*

Katie Clark, Katherine Koen, Emma L. Krueger, David A. Vanden Bout, The Univ. of Texas at Austin (United States)

Energy transport in organic systems is of interest for a variety of applications such as light harvesting for solar energy conversion. Results are presented for two fluorescence spectroscopy experiments that allow for direct measurement of energy transport in individual isolated organic nanosystems. Both take advantage of single particle spectroscopy techniques to examine the individual systems and quantify the maximum transport lengths. First, fluorescence imaging is used to probe the energy transport in tubular J-aggregates of well separated and bundled cylindrical 3,3'-bis- (2-sulfopropyl)-5,5',6,6'-tetrachloro-1,1'-dioctylbenzimida-carbocyanine (C8S3) dye. Transport was measured by exciting the aggregates with highly localized excitation followed by imaging the fluorescence emitting along aggregate. The one-dimensional average energy transport length was found to be 60 nm along well-separated cylindrical C8S3 J-aggregates. In sharp contrast, the bundle nanotubes exhibited transport on much longer length scales up to hundreds of nanometers. Second, transport was measured in single conjugated polymer chains and aggregates using super-resolution fluorescence microscopy combined with quenching by oxidation sites. Single chains of 1,049 kDa poly[2-methoxy-5-2-(ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV) were studied as their fluorescence was reversibly quenched by an applied bias to a capacitor-like device surrounding the molecules. By directly measuring the centroid of the emission from the polymer chain before and after quenching the spatial extent of the quenched regions could be measured in real space. The results show that large energy transfer distances (greater than 25nm) in single MEH-PPV chains were only observed in highly anisotropic conformations, and that these shifts are aligned with the longitudinal axis of the polymer.

9165-20, Session 5

The optical properties of conjugated materials and their aggregates: towards imaging films and devices

Linda A. Peteanu, Carnegie Mellon Univ. (United States); Jiyun Hong, Carnegie Mellon Univ. (United States) and Northwestern Univ. (United States); SuKyung Jeon, Janice Kim, Diane Devi, Carnegie Mellon Univ. (United States); Jurjen Wildeman, Zernike Institute for Advanced Materials (Netherlands); Matthew Y. Sfeir, Brookhaven National Lab. (United States); James H. Werner, Los Alamos National Lab. (United States); Andrew P. Shreve, The Univ. of New Mexico (United States)

Applications of conjugated polymers in photovoltaics and displays drive the need to understand how morphology affects emission and charge migration. A detailed analysis of the interactions that lead to aggregate-induced fluorescence quenching in conjugated polymers is challenging due to the heterogeneity of their structures. This drives recent efforts to analyze the effects of chain-chain interactions on the emission spectra via a detailed study of short-chain PPV- and thiophene-based oligomers and their aggregates. These are formed in solution by 'poisoning' a solution of the oligomers in a good solvent with a small amount of a poor solvent. They exhibit remarkably uniform spectral properties that vary reproducibly with the oligomer chain length and amount of poor solvent used in the preparation. This is verified by dispersed fluorescence microscopy of single aggregates. A more detailed probe of aggregate morphology is provided by fluorescence lifetime imaging (FLIM). The aggregate images are found to be consistent with the formation of "core-shell" structures in which the chains at the aggregate core are tightly packed and the chains at the surface are weakly interacting. This structural model of the single chain-aggregate interface rationalizes the bulk spectroscopic and lifetime data as well as data on the polymeric system. Our recent ultrafast studies probing the wavelength dependence of exciton-exciton annihilation dynamics and charge separation are also consistent with this morphological picture.

9165-21, Session 5

Carrier injection and dynamics from photoexcited transition metal containing porphyrins *(Invited Paper)*

Charles A. Schmuttenmaer, Rebecca L. Milot, Yale Univ. (United States); Gary F. Moore, Lawrence Berkely National Lab (United States) and Joint Ctr. for Artificial Photosynthesis (United States); Christian F. A. Negre, Victor S. Batista, Robert H. Crabtree, Gary W. Brudvig, Yale Univ. (United States)

Terahertz spectroscopy has proven itself to be an excellent non-contact probe of charge injection and conductivity with sub-picosecond time resolution. I will describe the charge injection time scale and efficiency for a selection of high-potential photoanodes (HPPAs) for photo-electrochemical cells. The anodes consist of bis- and tris-pentafluorophenyl free-base and metallo-porphyrin sensitizers anchored to TiO_2 and SnO_2 nanoparticles. Photoelectrochemical measurements demonstrate that the photosensitizers extend the absorption of the bare anode well into the visible region. THz spectroscopic studies demonstrate the sensitizers used in these HPPAs are capable of injecting electrons into the conduction band of the metal-oxide materials in those cases where the energies of the donor (excited state dye) and acceptor (metal oxide conduction band minimum) components are appropriate. The time scales and efficiencies are interpreted in terms of the identities

(singlet vs. triplet) and energetics of excited electronic states.

We have also investigated axially complexing bis-pentafluorphenyl Zn-porphyrin sensitizers to an isonicotinic acid anchor or variants thereof rather than binding them directly to the metal oxide surface. I will compare their binding stability in water, as well as their photoexcited interfacial electron transfer efficiency when using carboxylic acid, hydroxamate, acetylacetonate and phosphonate the anchoring group.

9165-22, Session 6

Two-electron photo-oxidation of betanin on titanium dioxide and potential for improved dye-sensitized solar energy conversion *(Invited Paper)*

Fritz J. Knorr, Washington State Univ. (United States); Deborah J Malamen, Washington State University (United States); Jeanne L. McHale, Washington State Univ. (United States); Arianna Marchioro, Jacques E. Moser, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Dye-sensitized solar photovoltaic cells based on plant pigments in the betalain family show promise for enhanced efficiency of solar energy conversion through two-electron photoredox chemistry of these pigments on nanoparticule TiO2. Solution phase betanin extracted from plants of the order Caryophylalles (such as beets and cactus pears) is known to undergo enzymatic and electrochemical two-electron oxidation. We have previously reported incident photon-to-current conversion efficiencies that suggest two electron photo-oxidation of betanin on TiO2. In this work, we pursue the spectroelectrochemistry and transient absorption spectroscopy of the violet pigment betanin adsorbed on nanocrystalline TiO2 to elucidate the mechanism of sequential or simultaneous two-electron injection. We report spectroelectrochemical evidence for two-electron proton-coupled oxidation of betanin on TiO2, resulting in a product with an absorption band in the blue. Transient absorption spectroscopy measurements on the nanosecond and femtosecond time scales were performed on betanin adsorbed on TiO2 and compared to similar measurements on non–injecting ZrO2 to reveal the spectral signatures and dynamics of oxidized species. Resonance Raman spectroscopic experiments of the photo-oxidation products will be presented in order to provide molecular insight into the photo-induced electron injection process.

9165-23, Session 6

The fate of photoinduced excitons and free carriers at carbon nanotube-fullerene interfaces

Andrew J. Ferguson, Anne-Marie Dowgiallo, Kevin S. Mistry, Bryon W. Larson, Jeffrey L. Blackburn, National Renewable Energy Lab. (United States); Dominick J. Bindl, Meng-Yin Wu, Michael S. Arnold, Univ. of Wisconsin-Madison (United States); Tyler T. Clikeman, Olga V. Boltalina, Steven H. Strauss, Colorado State Univ. (United States)

Photovoltaic active layers comprised of semiconducting single-walled carbon nanotubes (s-SWCNTs) in conjunction with buckminsterfullerene (C60) have realized power conversion efficiencies of around 1%, demonstrating their potential for low cost solar energy conversion applications. We employ a non-contact transient photoconductivity technique, time-resolved microwave conductivity (TRMC), to probe photoinduced free carrier generation, transport and decay at the s-SWCNT-C60 “bilayer” interface. Measurements of the mono-chiral (7,5) s-SWCNT-C60 interface highlight carrier generation and recombination rates that are dependent on the thickness of the (7,5) s-SWCNT layer. The former is due to the need for excitons in the SWCNTs to reach the interface with C60, whereas the latter can be attributed to partial penetration of the C60 into the s-SWCNT network, resulting in the formation of a graded or mixed interface. We subsequently turn our attention to the thermodynamics of free carrier generation at the s-SWCNT-fullerene interface. A study of a multi-chiral s-SWCNT/C60 interface shows that the efficiency of free carrier generation is determined by the diameter-dependent s-SWCNT bandgap, which alters the energetic offset between the electron affinities of the s-SWCNTs and C60 and hence the driving force for exciton dissociation to free carriers. We then remove uncertainties due to the presence of multiple s-SWCNT chiralities, by measuring (7,5) s-SWCNTs in conjunction with various perfluoromethylfullerene derivatives. Here we probe the dependence of free carrier generation on the electron affinity of the fullerene derivative. These two studies allow us to make further refinements to estimates of diameter-dependent electronic properties of s-SWCNTs.

9165-24, Session 6

Ultrafast electron transfer from low band gap conjugated polymer to quantum dots in hybrid photovoltaic materials *(Invited Paper)*

Elsa Couderc, Matthew J. Greaney, The Univ. of Southern California (United States); William Thornbury, USC (United States); Richard L. Brutchey, Stephen E. Bradforth, The Univ. of Southern California (United States)

We investigate the coupling of semiconductor quantum dots to complex organic environment. In organic materials, bound excited species are formed upon photo-excitation, and must be dissociated into free charge carriers for photovoltaic applications. Charge separation is typically achieved at an interface obtained by nanoscale mixing of electron accepting and donating phases. Hybrid solar cells contain quantum dots (QDs) as electron acceptors, but the performances of these heterojunctions remain low compared to those of all-organic cells. To better understand this discrepancy, we use ultrafast transient absorption to track the excited species on the QDs and polymer chains in the fs-ns range. Here, we study CdSe quantum dots blended with a low band gap polymer, poly[2,6-(4,4-bis-(2-ethylhexyl)-4H-cyclopenta[2,1-b;3,4-b?]dithiophene)-alt-4,7-(2,1,3-benzothiadiazole)]. Through selective excitation of the polymer, we show that the photo-generation of excitons on the polymer chains results in ultrafast electron transfer onto the quantum dots, detectable as an emerging spectral feature within our time resolution (65 fs). The yield of electron transfer depends on the QD surface chemistry, which participate in explaining the differences observed in photovoltaic performances for hybrids with different ligands. Finally, we find that very fast recombination (in the picosecond range) occurs in the hybrids. These results indicate that the performances of hybrids solar cells are not limited by charge carrier generation when ligands are properly chosen, but could be due to recombinations at longer times and to charge carrier extraction.

9165-25, Session 6

Quantum confinement-tunable ultrafast charge transfer at the PbS quantum dot and PCBM Fullerene interface

Omar F. Mohammed Abdelsaboor, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Flexible solar panels made from semiconductor quantum dots have great potential to be useful light-harvesting materials, opening up an optimistic view to utilize this new technology in third-generation photovoltaic devices1-3. More specifically, quantum dot (QD) solar cells have emerged as a promising low-cost alternative to existing photovoltaic technologies. Here, we investigate charge transfer and separation at PbS QDs and phenyl-C61-butyric acid methyl ester (PCBM) interfaces using a combination of femtosecond (fs) broadband transient absorption

(TA) spectroscopy and steady-state photoluminescence quenching measurements4. We analyzed ultrafast electron injection and charge separation at PbS QD/PCBM interfaces for four different QD sizes and as a function of PCBM concentration. The results reveal that the energy band alignment, tuned by the quantum size effect, is the key element for efficient electron injection and charge separation processes. More specifically, the steady-state and time-resolved data demonstrate that only small-sized PbS QDs with a bandgap larger than 1 eV can transfer electrons to PCBM upon light absorption. We show that these trends result from the formation of a type-II interface band alignment, as a consequence of the size distribution of the QDs. Transient absorption data indicate that electron injection from photoexcited PbS QDs to PCBM occurs within our temporal resolution of 120 fs for QDs with bandgaps that achieve type-II alignment, while virtually all signals observed in smaller bandgap QD samples result from large bandgap outliers in the size distribution. In other words, the electron injection process can be tuned from highly efficient and ultrafast (<120 fs) for PbS QDs with a bandgap of more than 1 eV to nearly or completely absent for QDs with larger diameters and a bandgap of less than 1 eV (See Scheme 1).

This information is of central importance to the design of photovoltaic devices employing QDs to harvest the near-IR solar spectrum. More generally, understanding the dynamics of the electron injection at the surface of the semiconducting QD is a key factor in determining the utility of these materials in applications that principally rely on the interfacial dynamics such as light-emitting diodes, p-n junctions, and photocatalysis.

9165-26, Session 7

Optical studies on metal oxide nanoparticles

Muneeswaran Muniyandi, National Institute of Technology, Tiruchirappalli (India); Mohammed Ghouse Munavary, National Institute of Technology Delhi (India); Giridharan Nambi Venkatesan, National Institute of Technology, Tiruchirappalli (India)

Multiferroic materials are attracting much attention due to their potential applications and their fascinating fundamental physics. $BiFeO_3$ (BFO) is the most intensively studied material due to its high ferroelectric Curie temperature (T_C)~1103K and antiferromagnetic Neel temperature (T_N)~643K. It has rhombohedrally distorted perovskite structure crystallized in space group of R3c. We here report the effect of the trivalent rare-earth ion, Dy^{3+}in the stabilization of the BFO phase, and investigating its structural, magnetic and optical properties. A soft chemical method has been adapted to synthesis single phase [$Bi_{1-x}Dy_xFeO_3$(BDFO x=0.0, 0.05, 0.10 and 0.15)] powders.The reaction precursors used were $Bi(NO_3)_3$•$5H_2O$, $Fe(NO_3)_3$•$9H_2O$ and $Dy(NO_3)_3$. H_2O powders. Distilled water was used as the solvent. By precisely controlling the chemical precipitation process, the reaction product was obtained. The product was washed and filtered by deionized water for several times then dried at 100 °C for 4 h and annealed at 600°C. The prepared BDFO powders were characterized by XRD, FT-IR, DRS and TEM. The details of the result will be presented and discussed.

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9165-27, Session 7

Effect of atomic under-coordination on the properties of Ag and Cu nanoclusters

Shideh Ahmadi, Xi Zhang, Nanyang Technological Univ. (Singapore); Yinyan Gong, China Jiliang Univ. (China); Changqing Sun, Nanyang Technological Univ. (Singapore)

Metallic nanostructures have attracted enormous interest recently due to their unique properties, which cannot be observed in the bulk counterparts, such as transition from conductor to insulator and nonmagnetic to magnetic and extraordinary high capability of catalysis. Density functional theory (DFT) calculations have been conducted to investigate the effect of the under-coordinated atoms in the surface region of the Cuboctahedral (CO) and the Marks decahedral (MD) structures of Ag and Cu nanoclusters. The calculation results are in good agreement with the experimental observations including X-ray-absorption fine structure (EXAFS), scanning tunneling microscope/ spectroscopy (STM/S), X-ray photoelectron spectroscopy (XPS), and ultraviolet photoelectron spectra (UPS). This consistency confirmed the predications based on bond order-length-strength correlation (BOLS) theory [1] and nonbonding electron polarization [2], suggesting that the shorter and stronger bonds between under-coordinated atoms in the surface skin of nanostructures induce local densification, entrapment of the core electrons, and valence charge polarization, which provide perturbation to the Hamiltonian and cause the new properties in Cu and Ag nanoclusters.

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9165-28, Session 7

Spectroelectrochemical photoluminescence of titanium dioxide nanosheets and nanoparticles in aqueous and nonaqueous environments

Riley E. Rex, Jeanne L. McHale, Fritz J. Knorr, Washington State Univ. (United States)

Spectroelectrochemical photoluminescence is used to investigate surface electron and hole traps on two different anatase particle morphologies in aqueous and nonaqueous environments. Trap state photoluminescence of nanocrystalline TiO_2 in aqueous environment under Fermi level control reveals the pH-dependent redox Fermi levels of the surface $Ti^{3+/4+}$ couple associated with five-fold coordinated titanium. In aqueous environment, this trap state distribution is populated at lower energy in TiO_2 nanosheets rich in exposed (001) surfaces, compared to commercial anatase TiO_2 nanoparticles with exposed (101) surfaces. Lower energy traps appear to be partially passivated in the case of nanosheets in acetonitrile environment. Self-modeling curve resolution of the photoluminescence under Fermi level control reveals three spectral components in aqueous and acetonitrile environments, the red and green photoluminescence we have previously associated with electron and hole traps, respectively, and a third intermediate (yellow) component that may result from a separate distribution of electron traps. An apparent overvoltage, which is larger for nanoparticles than nanosheets, is found for occupation of surface electron traps in aqueous environment. In contrast, electron traps in acetonitrile are occupied at potentials consistent with their energetic position within the band gap as determined by the photoluminescence spectrum. Our results reveal the solvent-dependent redox potential of electron traps and lend insight into the effects of contacting solvent on performance of nano-TiO_2 in applications such as dye–sensitized solar cells.

9165-29, Session 7

Charge trapping and intraband relaxation in colloidal quantum dot and perovskite photovoltaic materials *(Invited Paper)*

Artem A. Bakulin, FOM Institute for Atomic and Molecular Physics (Netherlands); Zhuoying Chen, Ctr. National de la Recherche Scientifique (France) and Ecole Supérieure de Physique et de Chimie Industrielles (France)

Solution-processed organic-inorganic hybrid materials like colloidal quantum dots (QD) or perovskites hold promise for cost-effective thin-film solar cells. The carrier dynamics in these materials is determined by the conduction and valence band structure, distribution of trapping states and the pathways for carrier relaxation. In current contribution, we apply a set of novel ultrafast electro-optical techniques, including Vis-pump – IR-probe, pump-push photocurrent, and 3-pulse transient absorption spectroscopies to elucidate the carrier relaxation and trapping dynamics in PbS QD and methylammonium lead halide perovskite films. The material properties were controlled by the QD ligand-exchange and perovskite surface passivation.

We show that the carrier relaxation in the studied systems can occur on a variety of timescales form 200 fs to longer than 10 ps. The particular charge relaxation and recombination rates strongly depend on the presence of defect states and the strength of electron-hole coupling. In QD photovoltaic device we observed that some photogenerated electron-hole pairs are intrinsically weakly bound. At the same time, charge diffusion in the QD films leads to substantial charge trapping on the ~ns timescale. Our study provides important information for the development and implementation of hot-electron extraction and carrier multiplication in third-generation photovoltaic devices.

9165-30, Session 7

Band-edge photophysics of emerging organic-inorganic photovoltaic materials

Robert J. Stewart, John B. Asbury, The Pennsylvania State Univ. (United States)

In both quantum dot and perovskite hybrid organic-inorganic photovoltaic materials, localized sub-gap states below the band edge may play important roles in mediating charge transport and in limiting the maximum obtainable photovoltage in solar cells. We present a systematic study examining the importance of these sub-gap states and their function in charge transport processes in quantum dot and perovskite materials using time-resolved infrared (TRIR) spectroscopy. Approaches are presented to eliminate sub-gap states by tuning the structure and composition of these hybrid materials in an effort to improve the short-circuit current and open-circuit voltage of the corresponding solar cells.

9165-31, Session 8

Time-resolved spectroscopy insights into charge transfer processes in organo-lead iodide perovskite solar cells *(Invited Paper)*

Jacques Moser, Arianna Marchioro, Ahmad A. Oskouei, Arun A. Paraecattil, Adrian Pulgarin, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Hybrid organic-inorganic lead halide perovskite semiconductors have recently been successfully applied as light absorbers in novel solid-state solar cells displaying a power conversion efficiency reaching 16% and an unprecedented open circuit voltage of 1.1 Volt. Ultrafast transient absorption spectroscopy and time-resolved terahertz photoconductivity measurements unraveled the mechanisms and dynamics of charge transfer processes taking place in titania and alumina mesoporous films impregnated with methylammonium triiodoplumbate (II) perovskite and the organic hole-transporting material (HTM) spiro-MeOTAD.

In photovoltaic systems based on a titanium dioxide | perovskite | HTM architecture, primary charge separation was observed by transient absorption in the NIR to occur at both junctions with the electron-transporting oxide and the HTM simultaneously, with ultrafast electron- and hole-injection taking place simultaneously.

The effect of the excitation wavelength upon the transient THz absorption amplitude and spectrum allowed evidencing the formation of excitons, polarons and bipolarons during the first picoseconds following pulsed excitation of the perovskite, on a time-scale slower than interfacial charge transfer. We thus conclude that the exceptionally large carrier diffusion lengths in the semiconductor allow photogenerated electrons and holes to reach the selective contacts separately, where they are readily injected, before they could associate in the form of excitons and eventually recombine. This unique charge separation mechanism makes perovskite hybrid solar cells a new type of photovoltaic converter of its own and a new realm of scientific investigation and technological development.

9165-32, Session 8

Ferroelectric domain walls as nanoscale pathways to novel functional properties *(Invited Paper)*

Patrycja Paruch, Univ. de Genève (Switzerland)

In ferroelectrics, domain walls separate regions with different polarization. At domain walls, modified symmetry and electronic structure, or chemical segregation can lead to unusual, extremely localized functional properties, quite different from those of the parent phase.

Particularly exciting has been the discovery of domain-wall-specific electrical conductivity in multiferroic $BiFeO_3$ [1]. Here, I will present our generalization of these observations to $Pb(Zr,Ti)O_3$ [2], highlighting the key role of oxygen vacancies, whose distribution can be modulated to reversibly control domain wall transport. For these studies, we have also developed carbon-nanotube-based probes with exceptional performance [3].

[1] Seidel, Nat. Mat. 8, 229 (2009)

[2] Guyonnet, Adv. Mat. 23, 5377 (2011)

[3] Lisunova, Nano Lett. 13, 4527 (2013)

9165-33, Session 8

The photophysics of perovskite solar cells *(Invited Paper)*

Tze Chien Sum, Nanyang Technological Univ. (Singapore)

Solution processed hybrid organic-inorganic perovskite solar cells have recently been identified as one of the breakthroughs of 2013. Power conversion efficiencies exceeding 15% from these devices have been reported.1, 2 These solar cells offer the promise of low-cost photovoltaics that is compatible with large-scale, low temperature processing. Remarkably, these phenomenal efficiencies were achieved in a matter of 4 years – up from ~3.8% back in 2009. Comparatively, dye-sensitized solar cells needed more than two decades of intensive research to achieve similar breakthroughs. In this talk, I will review the developments in these nanostructured perovskite solar cells and focus on the photo-physics and charge dynamics studies. I will discuss about our findings of long range balanced electron-hole diffusion lengths and the hot-hole cooling dynamics in $CH_3NH_3PbI_3$.3 I will also highlight some of our latest work on unravelling the charge dynamics and charge transfer mechanisms in these devices.

9165-34, Session 9

Optical properties of low bandgap copolymer PTB7 for organic photovoltaic applications *(Invited Paper)*

Uyen Huynh, Tek P. Basel, The Univ. of Utah (United States); Luyao Lu, Tao Xu, Tianyue Zheng, Luping Yu, The Univ. of Chicago (United States); Z. Valy Vardeny, The Univ. of Utah (United States)

We have measured the photoexcitation transient dynamics and magnetic field effect in pristine and donor-acceptor blends based on various low bang-gap polymers. We found that triplet excitons dominate the photoexcitation dynamics in both pristine and D-A blends. Therefore the charge photogeneration in the blends need not be simple exciton dissociation at the D-A interface, but may involve several novel avenues.

9165-70, Session 9

Exciton dynamics in disordered molecular environments *(Invited Paper)*

Adam P. Willard, Massachusetts Institute of Technology (United States)

For organic conjugated molecules details of the electronic structure such as excited state energy levels or spatial distribution of electronic charge depend sensitively on nuclear configuration. Consequently, for microscopically disordered systems like the bulk heterojunction predicting macroscopic electronic properties is a challenging and unsolved problem. We use molecular simulation to characterize the relationship between molecular disorder, both static and dynamic, and transient behavior of excitons in organic conjugated polymers and at donor-acceptor interfaces. In particular we carry out novel mixed quantum/classical simulations that are capable of providing a molecular-level basis for the interpretation of time-resolved ultrafast spectroscopic data.

9165-36, Session 10

Photoinduced charge separationp processes: from natural photosynthesis to organic photovoltaic cells

Oleg G. Poluektov, Argonne National Lab. (United States)

Photovoltaic (PV) cells are the most promising man-made devices for direct solar energy utilization. Detailed knowledge of the charge separation and charge transport in PV materials is crucial for improving the efficiency of the solar cells. Advanced EPR spectroscopy, especially light-induced multi-frequency EPR, has been essential for understanding the mechanisms of the light-induced generation, separation, and recombination of the charge carriers in natural photosynthesis. Here, we use light-induced EPR spectroscopy combined with DFT calculations to study mechanisms of charge separation and charge stabilization in active organic PV materials based on the composites of multiple polymers (P3HT, PCDTBT, and PTB7) and fullerene derivatives (C60-PCBM and C70-PCBM). Time-resolved EPR spectra show strong polarization pattern for all polymer-fullerene blends under study, which is caused by non-Boltzmann population of the electron spin energy levels in the radical pairs. Similar polarization patterns were first reported in molecular donor-acceptor systems, such as natural and artificial photosynthetic assemblies, and were understood within the models of spin-correlated radical pairs (SCRP) and sequential electron transfer. These models were used by us to explain the polarization pattern of the SCRP in polymer-fullerene blends and describe the charge separation process like electron jumps or tunnelling between neighbouring fullerene molecules. The first step of the charge separation process is exciton dissociation and electron transfer to the fullerene molecule neighbouring to the polymer. In order to outcompete the recombination process this state cannot live longer than a few picoseconds. Forward electron transfer forms an intermediate radical pair, with the separation distance within 15-20 Å. The third step is electron transfer to the secondary radical pair with a separation of 25-30 Å which is stable for tens-hundreds microseconds. The following electron transfer steps are on the slower time-scale and lead to further charge separation or charge recombination. The analysis presented here helps to improve our understanding of the mechanism of charge separation processes in the active organic photovoltaic materials.

9165-37, Session 10

Understanding electronic and optical properties of organic semiconductors from first principles *(Invited Paper)*

Leeor Kronik, Weizmann Institute of Science (Israel); Sahar Sharifzadeh, Lawrence Berkeley National Lab. (United States); Sivan Refaely-Abramson, Weizmann Institute of Science (Israel); Jeff B. Neaton, Lawrence Berkeley National Lab. (United States) and Univ. of California, Berkeley (United States)

Understanding the electronic and optical properties of organic semiconductors, with an emphasis on transport and optical gaps, is essential to the design of modern organic electronic and photovoltaic devices. Here, we show how this is achieved using a combination of density functional theory and many-body perturbation theory approaches. We then show how this sheds light on issues of direct relevance to device performance, such as inter-molecular hybridization, band dispersion, polarization phenomena, exciton formation and delocalization, and more.

9165-38, Session 11

Detection, tracking, and manipulation of individual biomolecules at interfaces *(Invited Paper)*

Jens Ehrig, Susann Spindler, Marek Piliarik, Ji Tae Kim, Vahid Sandoghdar, Max-Planck-Institut für die Physik des Lichts (Germany)

Some of the exciting challenges of modern biology and biophysics concern efforts to surpass the limits of conventional optical imaging. In particular, novel contrast mechanisms, sensitivity, signal acquisition rate and spatial resolution have been substantially improved over the past two decades. Over the past decade, we have developed interferometric scattering (iSCAT) microscopy as a fluorescence-free technique, which relies on measuring the interference of the Rayleigh scattering with a reference light beam.

In the first part of the talk, we report on using iSCAT to study the diffusion of very small gold nanoparticles (typically 20 nm) attached to GM1 or DOPE lipids in DOPC lipid bilayers at frame rates up to 1 MHz with nanometer precision [1]. We, thus, present a very powerful single particle tracking approach, with the potential to resolve some of the long-standing issues of the heterogeneities in lipid and protein compositions of cell membranes. Furthermore, we show that the sensitivity of iSCAT suffices to push the limits of biosensing by orders of magnitude to the detection of individual proteins as small as 60 kDa [2].

In the second part of the talk, we will introduce an electrostatic trap that is created in an aqueous medium between the aperture of a glass nanopipette and a glass substrate [3]. We demonstrate trapping and manipulating of nanoparticles or small biological entities like lipid vesicles. The ease of tuning the trap stiffness in real time by adjusting the height of the pipette allows on-command capture, displacement and release of nanoparticles.

References:

[1] Chia-Lung Hsieh, Susann Spindler, Jens Ehrig, Vahid Sandoghdar, Tracking single particles on supported lipid membranes: multi-mobility diffusion and nanoscopic confinement, J. Phys. Chem. B (2014); DOI: 10.1021/jp412203t.

[2] M. Piliarik and V. Sandoghdar, Direct optical sensing of single unlabeled small proteins and super-resolution microscopy of their binding site, arXiv:1310.7460v1 [physics.bio-ph] (2013).

[3] Ji Tae Kim, Susann Spindler, Vahid Sandoghdar, Scanning-aperture trapping and manipulation of single charged nanoparticles, Nat. Commun. (2014), accepted.

9165-39, Session 11

Super-resolution imaging reveals cooperativity and dynamics in live bacteria *(Invited Paper)*

Yi Liao, Krishanthi Karunatilaka, Julie S. Biteen, Univ. of Michigan (United States)

Single-molecule fluorescence brings the resolution of optical microscopy down to the nanometer scale, allowing us to unlock the mysteries of how biomolecules work together to achieve the complexity that is a cell. This high-resolution, non-destructive method for examining subcellular events has opened up an exciting new frontier: the study of macromolecular localization and dynamics in living cells. We have developed methods for single-molecule investigations inside live bacteria, and here, we discuss our investigations of DNA repair in Bacillus subtilis and starch digestion in Bacteroides thetaiotaomicron.

In the first case, we have examined mismatch repair (MMR), which corrects base-pairing errors in B. subtilis. Based on Photoactivated Localization Microscopy (PALM) of MutS-PAmCherry, two-color single-particle tracking (SPT), and mutant MutS defective for mismatch recognition and mismatch unbinding, we reveal the in vivo single-molecule distributions and dynamics of MutS, as well as the MutS-replisome interactions. Our results provide strong evidence that MutS recruitment to the replisome is required for MMR and precedes mismatch binding in vivo. In the second case, we have monitored the dynamics and cooperativity of recruits Starch-Utilization System (Sus) proteins in the prominent human gut symbiont B. thetaiotaomicron. By measuring the dynamics and stoichiometry of starch-induced Sus complex assembly on the molecular scale, we find that polymeric starches dynamically recruit Sus proteins, serving as an external scaffold for bacterial membrane assembly of the Sus complex, which in turn efficiently captures and degrades starch. Additionally, based on Sus protein knockout strains, we discern the mechanism of starch-induced Sus complex assembly.

9165-40, Session 11

Studies of structure and dynamics of protein-DNA complexes by single molecule and two-dimensional fluorescence spectroscopy (2DFS) *(Invited Paper)*

Andrew H. Marcus, Univ. of Oregon (United States)

The properties of biological macromolecules are greatly influenced by local soft interactions between proteins, nucleic acids, sugars and lipids. Such interactions affect the stability of biomolecular complexes, as well as the barriers that must be surmounted for molecular motions to occur. In this talk, I will present fluorescence based nonlinear spectroscopic measurements that determine the three-dimensional shapes, or local conformations, adopted by electronically coupled molecular dimers in biological environments. I will describe studies of the assembly of dimers of square-shaped metal tetraphenyl porphyrin (TPP) molecules embedded in a phospholipid bilayer membrane, in which we show that the assembled dimers exist as a “T-shaped” conformation. When a flexible linker is used to connect two TPP molecules, the “folded” form of the dimer is favored at elevated temperatures, which we show is due to entropic interactions between the TPP molecules and the local membrane environment. Similar experiments performed on dimers of fluorescent nucleic acid bases, which may be substituted for natural bases within model DNA constructs, reveal the structures of local base stacking conformations, and provide information about the balance of thermodynamic forces that contribute to nucleic acid stability. I will also describe single-molecule fluorescence experiments to investigate DNA ‘breathing’ fluctuations, in which nucleotide residues near single-stranded (ss) – double-stranded (ds) DNA forks and junctions temporarily adopt local conformations that depart from their most stable structures. Such fluctuations may comprise important mechanistic steps on the reaction pathways of a number of biological reactions important in DNA replication and RNA transcription.

9165-41, Session 12

Harmonic nanoparticles for nonlinear imaging and photo-interaction *(Invited Paper)*

Luigi Bonacina, Univ. de Genève (Switzerland)

The term harmonic nanoparticles designate a family of inorganic nanometric crystals (size < 100 nm) of different materials ($KNbO_3$, $BiFeO_3$, $LiNbO_3$, KTP, …) sharing the characteristic of noncentrosymmetric structure. This property determines their large nonlinear optical efficiency, and, in fact, in the last years they have been mostly investigated as localized sources for second harmonic generation. After introducing this approach and comparing it with respect to other nanoparticles-based labelling strategies (quantum dots, upconversion NPs), I will highlight some recent applications in the field of (multi-photon) imaging and optical detection of biological samples together with NPs-mediated photo-interaction with cellular DNA.

Nonlinear Nanomedecine: Harmonic Nanoparticles toward Targeted Diagnosis and Therapy, L. Bonacina, Mol. Pharmaceutics, 10, (3) 783-792 (2013)

Harmonic Nanoparticles for Cancer Theranostics, Davide Staedler et al., Nanoscale, 2013, Accepted Manuscript DOI: 10.1039/C3NR05897B

High-Speed Tracking of Murine Cardiac Stem Cells by Harmonic Nanodoublers, T. Magouroux et al. SMALL nano micro, 8 (17), 2752-2756 (2012)

Harmonic Nanocrystals for Biolabeling: A Survey of Optical Properties and Biocompatibility, D. Staedler et al., ACS Nano, 6 (3), 2542–2549 (2012)

9165-42, Session 12

Effect of solvent environment on colloidal quantum dot solar cell manufacturability and performance

Ahmad R. Kirmani, King Abdullah Univ. of Science and Technology (Saudi Arabia); Graham H. Carey, Univ. of Toronto (Canada); Buyi Yan, Maged Abdelsamie, Dongkyu Cha, King Abdullah Univ. of Science and Technology (Saudi Arabia); Lisa R. Rollny, Univ. of Toronto (Canada); Xiaoyu Cui, Canadian Light Source Inc. (Canada); Edward H. Sargent, Univ. of Toronto (Canada); Aram Amassian, King Abdullah Univ. of Science and Technology (Saudi Arabia)

State-of-the-art colloidal quantum dot (CQD) solar cells have been shown to achieve power conversion efficiencies (PCEs) approaching 9%. However, deposition of the CQD absorber layer is tedious requiring a layer-by-layer (LbL) buildup and is a major obstacle to industrial scale-up. Understanding why the LbL process is needed to achieve state-of-the-art devices is crucial to improving manufacturability and to improving solar cells further. In this study we have sought to evaluate the solvent-QD interactions in terms of physical and chemical changes to the CQD absorbing layer in order to identify an alternative and more facile ligand

exchange route. We have demonstrated that an extended exposure of CQD films to methanol (MeOH) is harmful for the overall performance. This explains why the standard CQD solar cells made with MeOH require tedious LbL buildup involving nearly a dozen steps. Understanding of solvent interactions with QD films has led us to develop more efficient processing conditions based on use of acetonitrile (ACN) which allow us to achieve state-of-the-art performance in only three steps. This work could shed light on ways to achieve a single step deposition and solid-state ligand exchange.

9165-43, Session 12

Exciton and carrier dynamics in quantum confined materials *(Invited Paper)*

Xiaoyang Zhu, Columbia Univ. (United States)

The best-understood property of quantum confined semiconductor systems, such as quantum dots, wires, and wells, is the quantization of charge carrier energies near the band edges. In contrast, much less is known about how quantum confinement and dimensionality affect carrier relaxation dynamics. Here we present recent efforts in our lab to quantitatively probe exciton and carrier relaxation dynamics in quantum confined systems. We apply femtosecond nonlinear spectroscopic techniques to directly follow the dynamics in energy and time domains. We show how charge carrier dynamics can be bulk like at high energies and how quantum confinement comes into play as these carriers cool down to near the band edges. We discuss the central role of enhanced Coulomb interaction in quantum confined systems in differentiating their dynamic behavior from those in bulk solids.

9165-44, Session 12

Quantum dots: using the known as well as exploring the unknown *(Invited Paper)*

Ron Tenne, Osip Schwartz, Ayelet Teitelboim, Pazit Rukenstien, Maria Dyshel, Weizmann Institute of Science (Israel); Taleb Mokari, Ben-Gurion Univ. of the Negev (Israel); Dan Oron, Weizmann Institute of Science (Israel)

Colloidal quantum dots (QDs) are a research focus in materials science as well as a promising building block for applications in optics and microscopy. I will describe two works portraying these two aspects in QDs research. In the first, synthesis of novel hetero-structures shed light on a long-lasting question regarding QD blinking. In a second work the “good-old” QDs serve as building blocks in a new superresolution microscopy technique relying on the quantum nature of light.

Single QDs exhibit switching between a dark and a bright emission state, a phenomenon termed blinking. While still a matter of debate, many models link this darkening to the Auger recombination in charged QDs. To investigate this claim a single inorganic hole trap was grown onto CdSe/CdS nanorods, stochastically charging the QD. Although charging indeed introduced an Auger recombination route, the trap addition increased only the occurrence of a third intermediate brightness (“grey”) level [1]. Together with other blinking studies, this work hints on the conditions required to avoid blinking and use QDs in new imaging applications.

Superresolution microscopy techniques, imaging of features below the Abbe diffraction limit, rely on breaking one of the assumptions made in the Abbe limit. While uniform illumination, linearity and time independence are the most common cornerstones of the Abbe limit bypassed, we have harnessed quantum fluctuations in light in order to achieve superresolution imaging, breaking the ‘classicality-of-light’ assumption [2].

[1]- ACS Nano, 2013, 7 (6), pp 5084–5090

[2]- Nano Lett., 2013, 13 (12), pp 5832–5836

9165-45, Session 13

High efficiency Perovskite solar cells based on organolead iodide *(Invited Paper)*

Nam-Gyu Park, Sungkyunkwan Univ. (Korea, Republic of)

(Invited Talk) Perovskite solar cell based on organolead halide has been considered as a promising photovoltaic technology because of very low cost and high efficiency, and thereby regarded as a potential alternative to silicon or CIGS solar cells. In this talk, technologies for perovskite solar cells with power conversion efficiency exceeding 16% are presented. Since the first report on long-term durable perovskite solar cell with power conversion efficiency (PCE) of 9.7% in 2012 by Park’s group, PCE increased rapidly, as a result, 15% was achieved by Gratzel and Snaith groups in 2013. However, the average PCE was as low as 12%. Deposition method was found to be critical to high efficiency devices. We compare the photovoltaic performance of methylammonium lead iodide perovskite solar cells prepared by one-step and two-step deposition methods, where one-step showed low PCE of about 8-9%, on the other hands, two-step methods showed higher PCE with average value of more than 15% and best value of 17%. Substitution of other organic cations for methylammonium led to lower band gap and higher absorption coefficient, which consequently resulted in PCE of 16% and average PCE of 15.5% with better photostability and little I-V hysteresis.

9165-46, Session 13

P-contact metal oxide in efficient $CH_3NH_3PbI_3$ perovskite/PCBM planar-heterojunction hybrid solar cells

Tzung-Fang Guo, Peter Chen, Jun-Yuan Jeng, Kuo-Cheng Chen, Tsung-Yu Chiang, Pei-Ying Lin, National Cheng Kung Univ. (Taiwan)

Applying a thin nickel-oxide (NiOx) interlayer between glass/ITO electrode and light absorbing CH3NH3PbI3 perovskite significantly enhances the photovoltaic performance of perovskite/fullerene-derivative heterojunction hybrid solar cells. The efficient hole transfer at NiO/perovskite heterojunction was verified by photo-induced absorption spectroscopy, showing a broad spectral feature above 800 nm, the long-lived charge-separation state of NiO+/P-. We successfully demonstrate the efficient hole transfer between NiO/perovskite junction and apply p-contact NiO for fabricating perovskite-based solar cells with decent efficiency. First, NiOx electrode-interlayer is a p-type semiconductor of high work function of 5.4 eV, which is close to the valence band edge level of CH3NH3PbI3 perovskite (5.4 eV). The alignment of energy level minimizes the interfacial energy losses for the hole transfer and optimizes the photovoltage output of device. Second, CH3NH3PbI3 perovskite films prepared by the spin-coating process on glass/ITO/NiOx substrate exhibit a relatively smooth morphology than those deposited on glass/ITO/PEDOT:PSS substrate. The conformal coverage of the perovskite film enhances the light harvesting, reduces the leakage current, increases JSC, and elevates the PCE of the devices. The best performing cell with the configuration of glass/ITO/NiOx/CH3NH3PbI3 perovskite/PCBM/bathocuproine/Al presents an VOC= 0.92 V, a JSC = 12.43 mA/cm2, and a FF = 0.68, corresponding to a PCE of 7.8 % under standard 1 sun AM 1.5G simulated solar irradiation. Our findings reveal the design principle for enhancing the photovoltaic performance of CH3NH3PbI3 perovskite/PCBM hybrid heterojunction solar cells through the judicious selection of metal oxide p-contact material.

9165-47, Session 13

Quantum-chemical calculations of hybrid inorganic-organic perovskites

Wichard J. D. Beenken, Mezhoura Oussadou, Harald Hoppe, Erich Runge, Technische Univ. Ilmenau (Germany)

We will present quantum-chemical calculations of hybrid organic-inorganic perovskites usable for photovoltaic devices using the programpackage VASP. Based on XRD structures for the inorganic part of the perovskite (e.g. PbI2) we will demonstrate the optimal positions of the organic cations (e.g. CH3NH4+), which are almost invisible for XRD, within this structure. Furthermore we will present band-structure calculations of the optimized structures.

9165-48, Session 13

Progress and fundamental insights into perovskite solar cells *(Invited Paper)*

Nripan Mathews, Nanyang Technological Univ. (Singapore)

Solid-state organic-inorganic perovskite (CH3NH3)PbX3 (X =Cl, Br, I) based nanostructured solar cells have recently gained a lot of attention due to their superior performance and ease of fabrication. At the lab scale, power conversion efficiencies over 15 % have already been achieved utilizing a solution based two-step method to deposit the perovskite A power conversion efficiency of ~ 17 % has been identified as a realistic target. Now that it has been shown conclusively that the CH3NH3PbX3 perovskite layers can form highly efficient solar cells, efforts must focus on two areas (i) Unravelling the reasons for the high efficiency and (ii) focussing on technologically relevant challenges.

The talk will cover these two broad areas. Physical and photophysical characterization of these classes of compounds will be presented. The relevance of these properties in determining the high efficiencies as well as in predicting newer structures of perovskites will be shown. Photophysical characterization results showing the excellent carrier lengths in these classes of compounds will also be described. On the technological side, a cost effective low cost roll-to-roll production of solid state devices is only possible when the processing temperatures are brought down to 100-150 oC. A low temperature approach can have other interesting advantages such as the fabrication of flexible devices, due to the instability of plastic substrates at high temperatures. The utilisation of a ZnO compact layer formed by electrodepositon and ZnO nanorods grown by chemical bath deposition (CBD) allow the processing of low-temperature, solution based and flexible solid state perovskite CH3NH3PbI3 solar cells. Conversion efficiencies of 8.90 % were achieved on rigid substrates processed at low temperatures. Other efforts to utilise various mesoporous architectures will also be covered.

9165-49, Session 14

Drug/protein interactions studied by time-resolved fluorescence spectroscopy *(Invited Paper)*

Thomas L. Gustavsson, Dimitra Markovitsi, Lab. Francis Perrin (France); Ignacio Vayá, Maria-Consuelo Jiménez, Miguel A. Miranda, Univ. Politècnica de València (Spain)

The transport and distribution of drugs in the body is a complex mechanisms governed by many different processes. An important role is played by specific transport proteins, responsible for the fixing and release of the drugs. Obtaining a better understanding of the factors that govern the structure and dynamics of drug-protein complexes is therefore of great interest.

Among the various experimental approaches used, time-resolved fluorescence spectroscopy has proven to be a particularly powerful tool. This technique informs on the excited state interactions occurring between the photo-excited drug and the protein, which in turn brings detailed information regarding the structural dynamics of the complex. In our laboratory, we use a combination of various fluorescence techniques, notably femtosecond fluorescence upconversion.

We report here on a recent time-resolved fluorescence study of the interaction between flurbiprofen (FBP), a chiral non-steroid anti-inflammatory drug, and human serum albumin (HSA), the main transport protein in the human body. We compare the results obtained for the drug-protein complex with those of various covalently linked flurbiprofen-tryptophan dyads having well-defined geometries. In all cases stereoselective dynamic fluorescence quenching is observed, varying greatly from one system to another. In addition, the fluorescence anisotropy decays also display a clear stereoselectivity. For the drug-protein complexes, this can be interpreted in terms of the protein microenvironment playing a significant role in the conformational relaxation of FBP, which is more restricted in the case of the (R)-enantiomer.

9165-50, Session 14

Protein structure following adsorption on nanoparticles: importance for cellular binding and uptake *(Invited Paper)*

Christine K. Payne, Sabiha Runa, Georgia Institute of Technology (United States)

Nanoparticles offer exciting new approaches for biomedicine ranging from drug delivery to cellular imaging. In the course of these applications, nanoparticles are exposed to a complex mixture of extracellular proteins that adsorb onto the surface of the nanoparticle. This “protein corona” dominates the interaction of nanoparticles with cells. We have investigated how proteins found in blood serum affect the cellular binding of protein-nanoparticle complexes. Using fluorescence microscopy, we find that the cellular binding of cationic nanoparticles is enhanced by the presence of serum proteins while the binding of anionic nanoparticles is inhibited. Competition assays confirm that these protein-nanoparticle complexes use distinct cellular receptors. Circular dichroism spectroscopy, fluorescence spectroscopy, and isothermal titration calorimetry show that the secondary structure of the adsorbed serum albumin is altered following adsorption on the surface of cationic nanoparticles. These structural changes redirect the albumin-nanoparticle complex to scavenger receptors. In comparison, the secondary structure of albumin is preserved following adsorption on anionic nanoparticles. The cellular binding trend is independent of nanoparticle composition: quantum dots, colloidal gold nanoparticles, and low-density lipoprotein particles all show the same behavior. This link between protein structure and cellular outcomes will provide a molecular basis for the design of nanoparticles for use in biomedical applications.

9165-51, Session 14

Interfacial self-assembly of the bacterial hydrophobin BslA *(Invited Paper)*

Cait MacPhee, Keith Bromley, Ryan Morris, Giovanni Brandani, Laura Hobley, The Univ. of Edinburgh (United Kingdom); Nicola Stanley-Wall, Univ. of Dundee (United Kingdom)

The Gram-positive soil bacterium, Bacillus subtilis, can assemble to form a biofilm, a community of bacteria supported and protected by a self-produced extracellular matrix. Biofilms created by B. subtilis are highly hydrophobic, a property that arises from the surface active protein BslA. The high interfacial activity and hydrophobic properties of BslA are due to its unusual amphiphilic structure, which was recently determined by X-ray crystallography. BslA in its purified form also forms stable, viscoelastic films at air- and oil-water interfaces, and has been likened to the fungal hydrophobins. I will describe the novel mechanism of self-assembly of BslA, and present the physical properties of the interfacial films.

9165-71, Session 14

Role of ZnS shell on stability, cytotoxicity and photocytotoxicity of water-soluble CdSe semiconductor quantum dots surface modified with glutathione

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Great efforts are currently devoted to fabricate high-quality quantum dots (QDs) in aqueous solutions for biomedical applications. Two biocompatible systems consisting of core (CdSe) and core/shell (CdSe/ZnS) QDs surface modified with glutathione (GSH), named CdSe-GSH and CdSe/ZnS-GSH respectively, were built. Upon photoirradiation using low laser power, both systems in HEPES buffer (pH:7.2) showed significant photoluminescence (PL) enhancements. CdSe/ZnS-GSH showed much less blue shifts in excitonic absorption and emission peaks without photobleaching compared with CdSe-GSH QDs system. X-ray diffraction showed that there is no change in the crystalline phase structure of the CdSe/ZnS-GSH QDs system after 1 h irradiation. Cell viability assessment, in the dark and following laser exposure, demonstrated that no cytotoxic effects were shown upon incubation CdSe/ZnS-GSH QDs with normal human skin (HFB4) or human adenocarcinoma (MCF-7) cell lines for periods up to 72 h and at concentrations up to 400 nM. The present study demonstrates that CdSe/ZnS-GSH QDs system exhibits a high photostability with a relatively high PL efficiency in aqueous medium following low intensity photoexcitation, without significant cytotoxic effect making this system attractive for several important biomedical applications.

9165-53, Session PWed

Contribution of weak localization and electron-electron interaction in corrective term mT1/2 of the metallic conductivity in p-type 70Ge:Ga

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We present measurements of the electrical conductivity of metallic samples 70Ge: Ga driven to the metal-insulator transition by impurity concentration, in the temperature range 0.53 to 0.017 K and with impurity concentration up to 2.6251017cm-3.The Electrical conductivity is found to behave like $\sigma=\sigma 0+mT1/2$ inferior to 17 mK. Physical explanation to the temperature dependence of the conductivity is given by considering the competition between two effects involved in the mechanisms of conduction, like electron-electron interaction effect, and weak localization effect. The data are for 70Ge: Ga sample prepared and reported by Kohei M. Itoh et al in reference ["Itoh, K. M,and al, Phys. Rev. Lett.77, 4058-4061 (1996)."].

9165-54, Session PWed

Crossover from Efros-Shklovskii to Mott variable range hopping in amorphous thin NixSi1-x films

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The temperature dependence of electrical conductivity of insulating amorphous NixSi1-x alloys is studied in the temperature range 1-160 K. At low temperatures, Efros-Shklovskii (ES) variable range hopping (VRH) is observed. This is assumed to occur because of the creation of the Coulomb Gap (CG) in the vicinity of Fermi level. With increasing temperature, CG vanishes and the measured conductivity can be described by Mott VRH model where the density of state is constant. The criterion of the crossover ES from to Mott VRH is assessed by extracting the related parameters.

9165-55, Session PWed

Transport phenomenon in two dimensional hole gas GaAs/AlGaAs

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In this work, we have studied the magnetoresistance in a dilute two-dimensional hole gas in GaAs/AlGaAs versus parallel magnetic field. To do this, we tried to define the normalized resistivity P(B)/P(0) as a function as B/Bx and B/Bcross, where Bx is a scaling parameter, and Bcross is determined by the crossover of B^2 dependence of theof the resistivity. This study shows that there is a dependence between the two curves of Bx and Bcross for various hole densities. Later, we were interested to extract the product m*g* for some values of hole density, in order to examine the variation of susceptibility x. The later is found to be almost constant for those values.

9165-56, Session PWed

Synthesis, Mössbauer spectroscopy and magnetic measurements of FeGa2O4 nanoparticles

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FeGa2O4 nanoparticles with mean crystallite sizes ranging from 1.8 to 28.0 nm were prepared by the combustion method. Room temperature Mössbauer spectra indicate that all iron ions in the sample of 1.8 nm are in the paramagnetic high spin ferric state Fe3+. The magnetic component appears in the spectra for the samples 2.4 nm, 5.4 nm, 12.3 nm and 28.0 nm along with the paramagnetic doublet. Relative content of the magnetic component increases with the increase in crystallite sizes. The appearing magnetic component has the isomer shift value typical of ferrous ions. This means that only Fe2+ ions are in a magnetically ordered state, while Fe3+ ions are paramagnetic in all samples at room temperature. The values of magnetic hyperfine field Hhf at Fe2+ ions are very low, which could be explained by superparamagnetic properties of small particles. Low temperature Mössbauer spectra of the 1.8 nm size particles indicate a magnetic ordering of all iron ions. The spectra can be fit to two magnetic components with different values of magnetic hyperfine fields. According to isomer shift values both components belong to Fe3+. At 5 K the values of the field Hhf are 463 and 402 kOe. These values can be attributed to Fe3+ ions in octahedral and tetrahedral sites of the spinel structure, respectively. We define the cation distribution over tetrahedral and octahedral sites: (Fe1/3Ga2/3)tet [Fe2/3Ga4/3]oct O4. With temperature increasing the value of Hhf decreases, and one can plot the temperature dependence of Hhf for both sites and indicate a Neel temperature of 20 K.

9165-57, Session PWed

Theoretical study in energy absorption in the systems zinc-macrocycles-nanocluster of TiO2 in solar-cells

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Many different principles have been proposed for constructing efficient solar-energy capturing devices. One of the more successful and promising approaches is dye-sensitized solar cells (DSSCs), proposed by Grätzel [1,2]. The chemical and physical processes of the Grätzel cells are largely known, whereas the details at the atomic level are less elucidated. To improve the efficiency of the dye-sensitized solar cells it is necessary to find suitable molecular chromophores for the light capturing process. We have studied from a point of view of quantum chemistry the process of interaction reduction of metallomacrocycles of Zn on cluster of TiO2 that represents the anatase surface [3-5]. Through calculations based on theoretical density functional (TDF) at the B3LYP, PBE y TPSS levels with dispersion effect, we study and quantify the interaction of the metallomacroclycle on the cluster of TiO2 and electronic spectra of the complexes in the energy absorption process.

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9165-58, Session PWed

A striking mobility improvement of C_{60} OFET by inserting diindenoperylene layer between C_{60} and SiO_2 gate insulator

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Gap states in organic semiconductors play a crucial role in determining Energy-Level Alignment and in many cases they act as charge trapping centers to result in serious lowering of charge mobility. Thus origin of gap states has gained increasong attention in order to realize higher mobility organic devises[1-4]. Bussolotti et al. have demonstrated recently that gap states in a pentacene thin film increase even by exposing the film to inert gas and confirmed that the gas exposure madiates structural defects in the film thus gap states[4]. The results have also indicated that preparation of better-ordered organic thin films is necessary to improve the device performance, namely to decrease trapping states.

Here we demonstrate a dramatic improvement of electron mobility (μn) of a C60-based OFET by using ultrathin diindenoperylene (DIP) as the template layer between the C60 layer and SiO2 gate insulator [5]. μn of the DIP-template C60 OFET shows 2.9 cm2V-1s-1, which is higher by about 15 times than the reference device without the DIP. Moreover striking device stability was also found for the DIP-template C60 OTFT upon air exposure. The DIP-template C60 OFET showed μn of 1.9 cm2V-1s-1 in air, whereas the C60 OFET without the DIP degraded completely in air. Grazing incidence X-ray diffraction revealed that the ultrathin DIP inter-layer between the C60 film and the SiO2 improves the C60 film quality in the crystallinity, crystal orientation and grain size at least factor of 3. Furthermore ultrahigh sensitivity UPS measurements demonstrated that lowering of the density of trap states in the C60 film as well as at the C60 interface for the DIP-template C60 film.

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9165-59, Session PWed

Preparation of flexible TiO_2 photoelectrodes for dye-sensitized solar cells

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Dye-sensitized solar cells (DSSCs) based on nanocrystalline TiO2 photoelectrodes on indium tin oxide (ITO) coated polymer substrates have drawn great attention due to its lightweight, flexibility, and advantages in commercial applications. However, the thermal instability of polymer substrates limits the process temperature to below 150 °C. In order to assure high and firm interparticle connection between TiO2 nanocrystals (TiO2-NC) and polymer substrates, the post-treatment of flexible TiO2 photoelectrodes (F-TiO2-PE) by mechanical compression was employed. In this work, Degussa P25 TiO2-NC was mixed with tert-butyl alcohol and DI-water to form TiO2 paste. F-TiO2-PE was then prepared by coating the TiO2 paste onto ITO coated polyethylene terephthalate (PET) substrate using doctor blade followed by low temperature sintering at 120 °C for 2 hours. To study the effect of mechanical compression, we applied 50 and 100 kg/cm2 pressure on TiO2/PET to complete the fabrication of F-TiO2-PE. The surface morphology of F-TiO2-PE was characterized using scanning electron microscopy. The resultant F-TiO2-PE sample exhibited a smooth, crack-free structure indicating the great improvement in the interparticle connection of TiO2-NC. Increase of compression pressure could lead to the increase of DSSC photoconversion efficiency. The best photoconversion efficiency of 4.19 % (open circuit voltage (Voc) = 0.79 V, short-circuit photocurrent density (Jsc) = 7.75 mA/cm2, fill factor (FF) = 0.68) was obtained for the F-TiO2-PE device, which showed great enhancement compared with the F-TiO2-PE cell without compression treatment. The effect of compression in DSSC performance was vindicated by the electrochemical impedance spectroscopy measurement.

9165-60, Session PWed

The influence of harmful gases on pentacene complexes

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We concentrated our efforts on the absorption of the harmful gases cited below. Analyzing the dissociation energy of PEC we found that just ultraviolet rays can dissociate the gas-pentacene bound. This is an important result because the absorption is effective. We observed that when we substitute some carbons of pentacene for inorganic compounds the absorption increases.

9165-61, Session PWed

Geometrical functionalization of carbon nanotubes

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Due to the importance of phenomena associated to carbon dioxide, this gas has since long ago attracted the attention of the scientific community. In order to solve this CO2 related environmental problems an accurate and reliable detection of this gas in a scale that allows mapping its concentration in any media is highly desirable. An efficient method to do so is the nanostructural arrestment of carbon dioxide (1). In this sense, carbon nanotubes stands (SWNT) up as a promising structure. Provided an important adsorption energy is observed between the gas molecule and the nanotube lattice, the other physical and chemical features of this system are favorable to this nanotechnology application. In a previous study, we observed that, whereas pristine SWNT present low reactivity, the effect of doping this system with transition metals yielded excellent results [2].In the present work, we propose a new route to functionalize SWNT in order to arrest carbon dioxide. By means of electronic structures calculations in the scope of the Density Functional Theory, we applied structural deformations to the lattice and conducted an analysis on whether or not the originated system was suitable to CO2 detection. The feasibility of this system to the actual application is measured in terms of the interaction energy, energies levels profiles and spectroscopic constants. By means of this procedure we observed a reasonable adsorption energy, of about an order of magnitude higher than that of the pristine nanotube. This indicate that the conformational functionalization is an reasonable choice to obtain efficient gas sensors.

9165-62, Session PWed

Silver nanoparticles on titanium dioxide through Linker molecules and its photocatalytic performance

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The development of metal-semiconductor photocatalyst through linker molecules makes innovation in catalytic materials. A controlled decoration of silver nanoparticles (AgNPs) through a linker molecule (HOOC-CH2-SH) on a titanium dioxide (TiO2) by Magnetron Sputtering was achieved. The structure, chemical nature, surface morphology and chemical bonding between the linker molecule, silver and titania have been characterized by UV-Vis Absorption Spectroscopy, Powder X-Ray Diffraction, Raman Spectroscopy, High Resolution Transmission Electron Microscopy and Field Emission Scanning Electron Microscopy. Combining the efficient photocatalytic activity of titania with the excellent absorption and electron acceptor abilities of AgNPs, it was possible to get a methylene blue (MB) photo-degradation of 100% at 150 min. The stability, particle-size and distribution of silver nanoparticles were controlled via chemical bonding to linker molecules and the sputter time.

The UV-Vis light photocatalytic activities were tested for the photocatalyst materials using the decoloration of MB solution. It was found that the best photocatalytic activity was obtained for TiO2-OOC-CH2-S-AgNPs with 30s of sputter time. The rest of photocatalysts prepared at different sputter times showed low performances, but higher than pure TiO2 nanoparticles. These results suggest that the use of linker molecules permit to control the particles size and distribution of AgNPs onto TiO2, allowing to modulate and improve the photocatalytic performance of TiO2.

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9165-63, Session PWed

The ESR and MCD studies of spinel $CuCr_2Se_4$ nanocrystals

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A facile solution based method involving the thermal decomposition of metal chloride precursors in selenium using oleyamine (OLA) as a solvent and stabilizing agent is used to synthesize spinel CuCr2Se4 nanocrystals. The Cu–Cr–OLA complex prepared at 175°C and cooled to room temperature (RT) is rapidly injected into Se–OLA mixture which has been heated to 330°C. The temperature of Se–OLA at time of injection is varied from 330°C down to RT. Transmission electron microscopy (TEM) images show 24.8 nm average size cubic to tetrahedron shaped nanocrystals prepared when the metal precursors were injected into the Se mixture at 330°C. Moreover, nearly monodisperse 68.1 nm hexagonal crystals prepared when injection was done at RT. X-ray diffraction (XRD) patterns show well defined crystalline peaks for samples provided the Cu: Cr: Se ratio was 1:2:8-10 (lack of excess selenium resulted in formation of secondary phases). The mean crystallite size from XRD matched well with TEM results. Hysteresis loops measurements show a soft ferromagnetic behavior with higher retentivity and magnetic saturation as the crystal size increased. A superparamagnetic relaxation is observed as the field-cooled (FC) and zero-field-cooled (ZFC) curves bifurcate while lower than bulk Curie temperature is a result of surface spin canting. The electron spin resonance (ESR) data shows hybridization between localized 3d3 electrons of Cr3+ and delocalized holes of Se 4p band, confirming correct phase formation. Broad magnetic circular dichroism (MCD) signals with similar shapes indicate magneto-optical effects of different crystal sizes.

9165-64, Session PWed

Ultrafast carrier trapping of metal-doped titanium dioxide semiconductor revealed with femtosecond transient absorption spectroscopy

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We explored for the first time the ultrafast carrier trapping of metal-doped titanium dioxide (TiO2) semiconductor using broadband transient absorption (TA) spectroscopy with 120 femtosecond (fs) temporal resolution. The titanium dioxide was successfully doped layer-by-layer with two metals namely Tungsten (W) and Cobalt (Co). The time-resolved data demonstrate clearly that the carrier trapping time decreases progressively with increasing the metal deposition time. A global fitting procedure for the carrier trapping indicates appearance of two time components: a fast one is directly associated with carrier trapping to the defect state in the vicinity of the conduction band while a slow component is attributed to carrier trapping to the deep level state from the conduction band. For a high doping deposition time in the range of 30 s, a carrier lifetime of about 1 picosecond is obtained. Interestingly, a significant effect not only of the doping deposition time but also the metal size on the carrier recombination dynamics is observed, indicating the crucial role of metal size in the carrier trapping in semiconductor oxides. Consequently, the findings reported here may potentially be implemented for high-speed optoelectronic applications and for ultrafast switching devices.

9165-65, Session PWed

The preparation of Pt nanoparticle counter electrode for dye-sensitized solar cells

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In dye-sensitized solar cells (DSSCs), a thin layer of platinum (Pt) on counter electrode (Pt CE) catalyzes the electron transfer process to hole conducting medium, such as iodide/triiodide redox couple. The surface microstructure of Pt CE is thus an important factor to determine the efficiency of DSSCs. In this work, the optimal condition for preparation of nanoparticle platinum (Pt) film was investigated in order to use it as the counter electrode for high efficiency DSSCs. Hexachloroplatinic acid (H2PtCl6•(H2O)6) was used as a Pt precursor and it mixed with ethyl cellulose, α-Terpineol, and ethanol, to prepare Pt paste. Pt CE was then prepared by screen printing the Pt paste onto FTO (fluorine-doped tin oxide) glass followed by thermal decomposition to form Pt nanoparticles on FTO (Pt nanoparticles counter electrode - Pt NP CE). The surface morphology of Pt NP CE was characterized using scanning electron microscopy (SEM). The resultant Pt NP CE sample exhibited a porous structure which could provide more active surface area for Pt catalysis process and reduces the charge-transfer resistance as well. The best photoconversion efficiency of 9.05 % (open circuit voltage (Voc) = 0.76 V, short-circuit photocurrent density (Jsc) = 16.93 mA/cm2, fill factor (FF) = 0.70) was obtained for the Pt NP CE device, which was 13 % enhancement compared with the sputter deposited Pt electrode based cell. The effect of Pt nanoparticles in DSSC performance was vindicated by the electrochemical impedance spectroscopy measurement.

9165-66, Session PWed

Interfacial electronic structure of colloidal PbS quantum dots

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Charge injection barrier and open circuit voltage (VOC) are affected by interfacial electron energy-level alignment in semiconductor Quantum dot (QD) solar cells. To keep the QDs stable and dispersive, surface ligand passivation is necessary, which adversely changes the electronic structure of QDs. Previously, only a few cases of literature have reported such electron structure changes by direct measurement of surface electron density of states, but their information is limited by vulnerable surface oxidation and low signal to noise ratio.

To investigate the electronic structure of lead sulfide (PbS) QDs and its effect of 1,2-Ethanedithiol (EDT) ligand passivation, we prepared colloidal quantum dots (CQDs) of PbS on two different substrates, indium tin oxide (ITO) and TiO2. They were transferred to a measurement stage for ultraviolet photoelectron spectroscopy (UPS) without air exposure and their electron density of states was observed. To discriminate the EDT contribution, we compared it with the results of PbS thin film and EDT exposure processed under vacuum. It is confirmed that the EDT adsorption induces the PbS more p-type characteristic. In addition, the chemical identification of each step was made by X-ray photoelectron spectroscopy (XPS)

The UPS spectrum for PbS CQDs comprises of five peaks from S 3s and 3p orbitals which are sensitive to oxidation. Their evolution and energy level alignment with the QD thickness are systematically observed by UPS and XPS. On ITO (WF = 4.62 eV), the PbS QDs show a slight hole injection barrier for Schottky type solar cells, whereas there is no electron injection barrier for heterojunction type but wide depletion layer on TiO2 (WF = 4.48 eV). However their actual energy level alignment with respect to Fermi level at ground state does not heavily depend on substrate. To enhance charge collection efficiency and increase VOC, a proper buffer layer or substrate treatment seems to be useful.

9165-67, Session PWed

Functionalized BNNTs as candidates to gas sensors

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It is a well-known fact that nanostructured materials are good candidates to gas sensors due to their good surface to volume ratio. Unlike Carbon Nanotubes (CNT), Boron Nitride Nanotubes (BNNT) tend to exhibit constant electronic properties regardless of the diameter, chirality and number of layers considered. Add that to the high oxidation and thermal resistances observed, greater chemical stability when compared to CNT, and fair temperature conductivity and one has an interesting class of system to nanotechnology applications particularly in harmful and oxidative environments in which CNT would not be so efficient. In order to assess the feasibility of a given system to an actual application, one must perform an accurate and thorough investigation of all the properties that might affect the systems behavior. In this sense, we investigate electronic and vibrational properties of pristine and cobalt doped single walled boron nitride nanotubes of different chiralities interacting with a carbon dioxide molecule through the use of the Density Functional Theory and the Discrete Variable Representation. A stronger interaction between the carbon dioxide molecule and the functionalized BN nanotube was observed, when compared to a similar simulation concerning carbon nanotubes. Density of states investigation suggest that the doping induces major changes in the electronic structure pattern in the sense of critically reducing the original gap. From the vibrational point of view we note that the zig-zag chirality tends to present higher values of vibrational frequencies for most of the states considered regardless of the nanotubes being doped or not. Our results leads one to consider functionalized BN nanotubes superior to their carbon equivalents as far as chemisorption phenomena is concerned.

9165-68, Session PWed

Dynamics of exciton diffusion in organic semiconductors

Pedro H. Neto, Wiliam F. Cunha, Guilherme M. Carvalho, Univ. de Brasília (Brazil)

The phenomenological reasons behind the decay of the luminescence observed in organic based compounds are unclear. By means of time-resolved photoluminescence in conjugated polymer/fullerene heterostructures was suggested that a single exciton diffusion coefficient can be utilized as a descriptive parameter for the dynamics of excitation migration in conjugated polymers. However, the heterogeneous morphology of thin films based on conjugated polymers makes difficult to separate the effects of chain conformation and interchain contacts from the intrinsic electronic properties of the chain. In this context, we investigated the creation of excitons and their dynamics in organic semiconductors with a modified version of the Su-Schrieffer-Heeger model Hamiltonian to include temperature effects and photoexcitations. When it comes to the excitons dynamics solely considering temperature, it was possible to characterize the diffusive process of the quasiparticles as being mainly due to random-walk effect, rather than being primarily originated from a concentration gradient. The good agreement with experimental evidences allows us to conclude that our model is, in many aspects, a fundamental tool to the phenomenological understanding of the charge-transport behavior in this class of new materials

9165-69, Session PWed

Optical tunability of magnetic polaron stability in single-Mn doped bulk GaAs and GaAs/AlGaAs quantum dots

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Optical control of magnetic property of a magnetic polaron (MP) in Mn-doped bulk GaAs and GaAs/AlGaAs quantum Dots (QDs) have been studied. We have developed basis optimization technique for the method of linear combination of atomic orbitals (LCAO), which significantly improve the accuracy of the conventional LCAO calculation. We have demonstrated that a monochromatic, linearly polarized, intense pulsed laser field induces a collapse of the MP and an ionization of Mn-acceptor in Mn-doped GaAs materials due to a dichotomy of hole wave func tion. We find this optical tunability of MP stability can be adjusted by confinement introduced in GaAs QDs.

9166-1, Session 1

Some emerging directions in 21st century medicine *(Invited Paper)*

Massoud H. Agahi, Harbor-UCLA Medical Ctr. (United States); Farnaz Haji, Midwestern Univ. (United States)

"Nanomedicine" has been a term used loosely to refer to an emerging field of nano-scale technologies and concepts that may enable advances in the health sciences. The Nanomedicine initiative of the NIH Common Fund was established as a 10 year program with the primary goal of "characterizing the molecular components inside cells at a level of precision that leads to re-engineering intracellular complexes." At the midpoint of the Program the Nanomedicine Development Centers were asked to "define their translational goals and the transitional research path needed to reach those goals by the end of the initiative in 2015."

As Nanomedicine develops beyond its infancy stage it is necessary for those involved in related research and development activities to become aware of the general trends and trajectories in the field in order to better align their own efforts. Highlights of the NIH initiative will be discussed along with other leading developments of interest to researchers who envision contributing to this exciting transformation in the health sciences. Finally, some general thoughts and introduction to specific problems in clinical medicine that may be suitable targets for the emerging technologies to address will be presented.

9166-2, Session 1

Intracellular delivery of p53 gene, siRNAs against oncogenes and anti-cancer drugs using pH-sensitive inorganic nanoparticles for induction of apoptosis in breast cancer cells

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Taking into account the high mortality and relapse rates of breast cancer, a new discipline maneuvering the heterogeneous biology of breast tumors and interfering with the underlying pathways would be an unmet need in breast cancer management.

This study utilizes carbonate apatite nanoparticles, as an efficient macromolecular drug delivery and expression system, for in vitro and in vivo intracellular delivery of p53 gene and siRNAs against HER2, MAP kinase and PI3 kinase pathway genes into breast cancer cells. By enhancing the capacity of the breast cancer cells to undergo apoptosis, this approach is shown to render the cancer cells more sensitive to classical anti-cancer agents.

The efficacy of the proposed treatments is evaluated by means of cytotoxicity assays, western blotting and also tumor regression studies in tumor bearing mice.

9166-3, Session 1

Incorporation of photosenzitizer hypericin into synthetic lipid-based nano-particles for drug delivery and large unilamellar vesicles with different content of cholesterol

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It has been proven that low-density lipoproteins (LDL) are useful vehicles for lipophilic drugs to cancer cells. We have used modified dextran (Dm) as protective coating of the natural LDL (nLDL) as well as of the synthesized LDL (sLDL) surface to make this delivery system even more efficient. In using the hydrophobic natural photosensitizer hypericin (Hyp) we intend to show that such modification can reduce the interaction of the initial [LDL-drug] complex with other serum constituents, such as free lipoproteins, and consequently decrease the drug redistribution processes.

Cryo-electron microscopy was used to characterize the size and structure of the complex. Fluorescence spectroscopy, confocal fluorescence imaging, raman optical tweezer and flow cytometry were used to characterize the redistribution of Hyp, loaded in lipoprotein/Dm complexes to free LDL molecules as well as to monitor cellular uptake of Hyp by U87-MG cells. It was shown that the redistribution process of Hyp between nLDL or sLDL molecules is partially decreased by Dm coating of (n/s)LDL surface. However, dextran coating of LDL-Hyp does not inhibit their recognition by LDL receptors of U-87 MG cells and further uptake of Hyp. Hence, this approach could lead to the construction of effective and selective delivery system of hydrophobic drugs to cancer cells.

9166-4, Session 1

Targeting hepatocellular carcinoma with aptamer-functionalized PLGA/PLA-PEG nanoparticles *(Invited Paper)*

Shannon E. Weigum, Melissa Sutton, Eugenia Barnes, Texas State Univ. (United States); Sarah Miller, New Braunfels High School (United States); Tania Betancourt, Texas State Univ. (United States)

Hepatocellular carcinoma (HCC) is one of the leading causes of cancer-related death worldwide, particularly in regions where chronic Hepatitis B and C infections are common. Nanoparticle assemblies that incorporate high –affinity aptamers which specifically bind malignant hepatocellular carcinoma cells could be useful for targeted drug delivery or enhancing contrast with existing ablation therapies. The in vitro interactions of a tumor-specific aptamer, TLS11a, were characterized in a hepatoma cell line via live-cell fluorescence imaging, SDS-PAGE and Western Blotting techniques. Cell surface binding of the aptamer-AlexaFluor®546 conjugate was found to occur within 20 minutes of initial exposure, followed by internalization and localization to early endosomes using the pH-sensitive LysoSensor™ Green dye and confocal microscopy. Aptamer-functionalized poly(lactide)-b-poly(ethylene glycol) (PLA-PEG) polymer nanoparticles were then prepared by nanoprecipitation and passively loaded with the chemotherapeutic agent, doxorubicin, yielding spherical nanoparticles approximately 70-100 nm in diameter. Targeted drug delivery and cytotoxicity was assessed using live/dead fluorescent dyes and a MTT colorimetric viability assay with elevated levels of cell death found in cultures treated with the aptamer-targeted PLA-PEG nanoparticles. Identification and characterization of the cell surface protein epitope(s) recognized by the TLS11a aptamer are ongoing, but these preliminary studies support the use of this unique aptamer and functionalized nanoparticle conjugates for targeted labeling and drug delivery within malignant hepatocellular carcinomas.

9166-5, Session 1

Nanotechnology-based treatment for chemotherapy-resistant cancer

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Background: Treatment of metastatic cancer remains a formidable clinical challenge. Better therapeutic options with improved tissue penetration and tumor cell uptake are urgently needed. Targeted nanotherapy, for improved delivery, and combinatory drug administration aimed at inhibiting chemo-resistance may be the solution.

Purpose: The study was performed to evaluate the therapeutic efficacy of polymeric PEG-PE micelles, co-loaded with curcumin (CUR) and doxorubicin (DOX), and targeted with anti-GLUT1 antibody (GLUT1) against MDA-MB-231 human breast adenocarcinoma cells both in vitro and in vivo.

Methods: MDA-MB-231 DOX-resistant cells were treated with non-targeted and GLUT1-targeted CUR and DOX micelles as a single agent or in combination. Tumor cells were also inoculated in female nude mice. Established tumors were treated with the micellar formulations at a dose of 6 mg/kg CUR and 1 mg/kg DOX every 2 d for a total of 7 injections.

Results: CUR+DOX-loaded micelles decorated with GLUT1 had a robust killing effect even at low doses of DOX in vitro. At the doses chosen, non-targeted CUR and CUR+DOX micelles did not exhibit significant tumor inhibition versus control. However, GLUT1-CUR and GLUT1-CUR+DOX micelles showed a significant tumor inhibition effect with an improvement in survival.

Conclusion: We showed a dramatic improvement in efficacy between the non-targeted and GLUT1-targeted formulations both in vitro and in vivo. Also, importantly, the addition of CUR to the micelle, has restored sensitivity to DOX, with resultant tumor growth inhibition. Hence, we confirmed that GLUT1-CUR+DOX micelles are effective in vitro and in vivo and deserve further investigation.

9166-6, Session 1

Feedback-mediated cancer therapy: a FRET-based nanoreporter approach

Suproteem K. Sarkar, Conestoga High School (United States) and Brigham and Women's Hospital (United States); Yashika Khater, Brigham and Women's Hospital (United States); Ashish Kulkarni, Shiladitya Sengupta, Harvard Medical School (United States)

A theranostic nanoparticle system was developed by integrating a chemotherapeutic agent with an "activatable" fluorescent tracer. The system signals tumor death by monitoring the activity of caspase-3, a product of apoptosis.

The polymer nanoparticles (Poly [isobutylene-alt-maleic anhydride]) were formed through reprecipitation and contained paclitaxel, a chemotherapy drug, and fluorescein isothiocyanate, a fluorescent dye. The dye's fluorescence was quenched through Förster resonance energy transfer (FRET) by a quencher that was connected to the dye by a peptide chain. With sizes ranging from 250-300 nm, the nanoparticles were stable for two weeks.

The nanoparticles were tested in vitro with responsive Lewis Lung Carcinoma (LLC) cells and taxane-resistant cells. Upon cell death by paclitaxel exposure, caspase-3 cleaved the peptide chain connecting the dye and the quencher, causing the system to fluoresce. When LLC cells were treated with the system, the nanoreporters fluoresced, but when resistant cells were tested, and when the drug was removed from the system, the nanoreporters did not fluoresce.

Since the system screens if a drug can successfully kill a particular tumor, it offers a novel and promising approach to personalized medicine.

9166-8, Session 1

Gold nanorods coupled with upconversion phosphors for simultaneous bladder cancer detection and treatment

Suehyun K. Cho, Univ. of Colorado at Boulder (United States); Lih-Jen Su, Xiaoping Yang, Thomas W. Flaig, Univ. of Colorado Denver (United States); Wounjhang Park, Univ. of Colorado at Boulder (United States)

The development of multifunctional nanoparticle complex composed of upconversion phosphor (UCP) nanoparticles and gold nanorods (AuNR) is presented. The anti-epidermal growth factor receptor antibody (αEGFR) conjugated AuNRs were prepared to demonstrate (1) specific binding to the EGFR-expressing bladder cancer cells (HTB9) and (2) thermal ablation of the cells upon NIR irradiation. The successful conjugation of AuNRs with αEGFR was directly confirmed by the specific binding to the HTB9 cells via NIR darkfield microscopy. In vitro thermal ablation experiments showed effective and selective cell killing by NIR irradiation.

UCPs absorbing NIR light and emitting visible fluorescence have ample potential as a high-contrast bio-imaging agent as the NIR excitation invokes minimal autofluorescence. For bioconjugation, UCPs were grafted with thiol and amine ended heterofunctional polyethylene glycol and poly(maleic anhydride-alt-1-octadecene) (PMAO). PMAO was first attached on UCP by hydrophobic interaction. Subsequent reaction with the amine group of PEG turns PMAO amphiphilic and the UCP nanoparticles water-soluble. The remaining amine-reactive groups allow further functionalization with αEGFR which provides specific, targeted binding with HTB9 cells.

The HTB9 cells treated with αEGFR functionalized UCPs were examined by fluorescence microscopy under 980nm illumination and membrane binding was clearly observed.

Finally, by using the free thiol end of PEG attached on UCP, the αEGFR functionalized UCP was linked to AuNR. The formation of UCP-AuNR complexes was confirmed by both optical microscopy as well as electron microscopy. Successful UCP-AuNR coupling enables simultaneous cellular level detection and ablation of cancer, opening a door to new diagnostic and therapeutic approaches.

9166-9, Session 1

Plasmonic enhanced pulsed laser induced optoporation and transfection of cells *(Invited Paper)*

Michel Meunier, Ecole Polytechnique de Montréal (Canada)

A new technique is introduced to perform optoporation and transfection of living cells using a laser and nanotechnology. Irradiating plasmonics nanostructures by an ultrafast laser beam produces highly localised processes on the nanoscale in the biological surrounding medium, yielding to the optoporation of the cell membrane.. These nanoparticles could be functionalised to target specific biological entities, thus performing multiple targeted processes on the nanoscale. . We are able to perform gene transfection in living cell with an optoporation efficiency as high as 70%. Complete physical model was developed to determine the basic mechanism underlying this new process. Our laser technology shows promises as an innovative tool for fundamental research in biology and medicine as well as an efficient alternative nanosurgery technology that could be adapted to therapeutic tools in the clinic.

9166-10, Session 1

Controlling the intracellular fate of nano-bioconjugates: pathways for realizing nanoparticle-mediated theranostics *(Invited Paper)*

James B. Delehanty III, Christopher M. Spillmann, Jawad Naciri, Kimihiro Susumu, Michael H. Stewart, Alan Huston, U.S. Naval Research Lab. (United States); Philip E. Dawson, Juan B. Blanco Canosa, The Scripps Research Institute (United States); Igor L. Medintz, U.S. Naval Research Lab. (United States)

For nanomaterials to realize their full potential in disease diagnosis and drug delivery applications, one must be able to exert fine control over their cellular delivery, localization and long-term fate in biological systems. Our laboratory has been active in developing methodologies for the controlled and site-specific delivery of a range of nanomaterials (e.g., quantum dots, colloidal gold, nematic liquid crystals) for cellular labeling, imaging and sensing. This talk will feature several examples from these efforts and will highlight the use of peptide- and protein-mediated facilitated delivery of nanomaterials to discrete cellular locations including the endocytic pathway, the plasma membrane and the cellular cytosol.

9166-11, Session 2

Probing protein-nanoparticle interactions using a plasmon waveguide resonance

Farshid Bahrami, Univ. of Toronto (Canada); Mathieu Maisonneuve, Michel Meunier, Ecole Polytechnique de Montréal (Canada); Arthur O. Montazeri, Yujin Kim, Nazir P. Kherani, James S. Aitchison, Mohammad Mojahedi, Univ. of Toronto (Canada)

A plasmon waveguide resonance (PWR) sensor is proposed for studying gold nanoparticle-protein interactions. The polarization diversity of the PWR sensor enables simultaneous measurement of surface reactions with two different light polarizations – TM and TE. Gold nanoparticles are immobilized on the PWR surface using a self-assembled APTMS layer. Then, nanoparticles are biotinylated and two different concentrations of streptavidin are passed over the samples. The response of each mode to streptavidin-biotin interaction at the surface of gold nanoparticles is investigated in real time. Finally, the nanoparticle surface reaction is decoupled from the bulk solution refractive index variations using dual mode spectroscopy.

9166-12, Session 2

Redox colorimetric-polyaniline nanoindicator for in-situ trafficking of intracellular transport

Seo Ryung Bae, Jihye Choi, Hyun-Ouk Kim, Byunghoon Kang, Myeong-Hoon Kim, Jong-Woo Lim, Yonsei Univ. (Korea, Republic of); Jin-Suck Suh, Yong-Min Huh, Yonsei Univ. College of Medicine (Korea, Republic of); Seungjoo Haam, Yonsei Univ. (Korea, Republic of)

Real-time tunable ratiometric fluorescent proton organic sensor that can efficiently measure optical fluorescent-based ratiometric signals in living cells, have attracted much interest in an aspect of understanding diverse cellular processes. In particular, vesicular proton plays a crucial role in cell biology staying generally between 6.8 and 7.4 in the cytosol and between 4.5 and 6.0 in the cell's acidic organelles since proteins depend on the proton level to maintain their structure and function, and cellular dysfunction is often associated with an abnormal proton level in organelles. One promising approach is the assessment of a nanoindicator based on polyaniline (PANI) that exhibits convertible transition states according to proton levels. To synthesize monodisperse silica-coated PANI for trafficking of the intracellular compartment with varying proton gradients, Fe3O4–MnO heterostructured nanoparticles were employed as an oxidant for the polymerization of aniline in an aqueous acidic medium. We synthesized two partially reversible oxidized forms of PANI, the deprotonated EB and protonated ES states, which exhibit distinct absorbance peaks at 750 and 600 nm, respectively. Subsequently, two pH-insensitive fluorophores, Cy3 and Cy7 were further adsorbed onto the PANI surface. The optical-absorbance peak of polyaniline was red-shifted as a result of its transition from the EB state to the ES state in the entire physiologically relevant range of the endosome–lysosome pathway. To assess the feasibility of using a fluorophore-adsorbed silica-coated polyaniline nanoindicator (FPSNI) as an organic nanoquencher, we investigated the quenching effect of FPSNICy3 and FPSNICy7, biocompatibility, and in vitro ratiometric fluorophores intensities.

9166-14, Session 2

Novel nano-optical concepts for sensing and driving helical micro-biological objects

Silke R. Kirchner, Lindsey L. Anderson, Ludwig-Maximilians-Univ. München (Germany); Debora Schamel, Max-Planck Institut für Intelligente Systeme (Germany); Spas N. Nedev, Sol Carretero-Palacios, Andreas Mader, Madeleine Opitz, Theobald Lohmüller, Ludwig-Maximilians-Univ. München (Germany); Peer Fischer, Max-Planck Institut für Intelligente Systeme (Germany) and Univ. Stuttgart (Germany); Jochen Feldmann, Ludwig-Maximilians-Univ. München (Germany)

We report two novel concepts related to optical trapping that have great potential for future applications in theranostics on the micro- and nanoscale.

Recently, an optically based "nanoear" has been introduced by our group [1] which allows for the detection of flagellar motion stemming from an optically trapped bacterium [2]. For this purpose a single bacterial cell either with or without a helical flagellar bundle is optically trapped in a focused laser beam. A second optical tweezer is used to trap a silica particle close to the trapped bacterium. The spatiotemporal diffusion pattern of the microparticle within the tweezer potential is then tracked with the help of a dark field microscope and a high speed camera. The Fast-Fourier spectrum of the particle motion clearly shows a resonance at 62 Hz which is interpreted as the main rotation frequency of the flagellar bundle [2].

Vice versa, we study the light-induced rotation of a helical colloidal silica particle [3, 4] which serves as an inorganic model system of a rotating bacterial flagellum. Here, the inorganic colloidal screw-propellers are held in an optical trap. We obtained the rotation frequency by performing a Fast-Fourier analysis of the optically detected microscrew position versus time. Although the incident light is linearly polarized, the helical shape of the particle results in rotation. We can drive the "micro driller`s" rotation even more efficiently when using circularly polarized light.

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9166-15, Session 2

Transfer of electronic excitation energy in determining of structural changes in nanoscale biosystems under the influence of surfactants

Andrey G. Melnikov, Irina V. Alonova, Gennady V. Melnikov, Saratov State Technical Univ. (Russian Federation)

We observed singlet-singlet energy transfer between tryptophanyl of human serum albumin (HSA) and probes from xanthene and acridine series.

We determined the radius of singlet-singlet energy transfer between tryptophanyl and the probes from xanthene series. The values of this radius do not exceed a value of 10 Angstroms. This indicates that the selected hydrophilic probes are localized in deep microregions of protein globule near hydrophobic tryptophanyl. The efficiency of energy transfer between tryptophanyls and probes from xanthene series: eosin, erythrosine is much higher than between tryptophanyls and trypaflavine.

We have studied the interaction of the cationic (cetyltrimethylammonium bromide), anionic (sodium dodecyl sulfate) and nonionic (triton X-100) surfactants with proteins. We observed the decrease in the radius of energy transfer during surfactants addition, which testifies about structural changes in proteins under the influence of surfactants. Hence the radius of energy transfer is a quantitative assessment of structural changes in proteins.

In addition, the binding constants of probes with proteins were identified.

Also we performed studies of triplet-triplet transfer of electronic excitation energy through the exchange- resonance mechanism between the polar probes – energy donor – eosin and nonpolar probes – energy acceptors – anthracene bound to HSA. These studies have revealed interglobular energy transfer due to diffusion of the energy donor – eosin during the lifetime of its excited triplet state in protein solution.

Radius of triplet-triplet energy transfer was defined. The dependence of the radius of energy transfer on the concentration of surfactants that causes structural changes in proteins was observed.

9166-16, Session 2

Portable biosensor based on plasmonic interferometer array

Xie Zeng, Dengxin Ji, Nan Zhang, Haomin Song, Qiaoqiang Gan, Univ. at Buffalo (United States)

High-throughput microarray multiplexed biosensing is important for early detection of disease and drug screening, which currently rely on fluorescent-labeling techniques. However, since fluorescent labels often interfere with molecular binding interactions and lead to inaccurate measurement, there is a significant need for label-free biosensing technique. While prism-based surface plasmon resonance systems have become the archetype for label-free biomolecular and chemical sensing, reductions in size and instrumental complexity are desired for applications requiring low-cost, compact, portable sensors, including routine point-of-care clinical evaluation, real-time diagnosis of diseases in developing countries and fast genetic mapping for personalized care. Nanoplasmonic biosensors employing novel topographies are an attractive miniaturized platform to meet these requirements, which are mainly based on wavelength interrogation in most reports. However, high spatial density multiplexed measurements are difficult to achieve in these designs in that broadband wavelength analysis via spectrometer is required, which inevitably adds the size and cost of the entire sensing system. In this work, we develop a compact plasmonic interferometer biosensor platform constructed by nanogroove-slit pairs or nanogroove rings with a nanohole at their center. Surface plasmon modes generated at the nanogrooves will propagate to the nanoslit or hole to interfere with the free space light transmitted through the nanoslit/hole and enable the surface refractive index sensing. Importantly, this plasmonic interferometer can be fabricated in a large scale array and be directly imaged by miniaturized microscope system coupled with CCD/CMOS imagers to realize low cost and portable sensitive multiplexed biosensor systems.

9166-17, Session 2

Label free detection of phospholipids by infrared absorption spectroscopy

Tahsin Ahmed, Erick Foster, Genevieve Vigil, Aamir A. Khan, Paul W. Bohn, Scott S. Howard, Univ. of Notre Dame (United States)

We present a new compact, label free dissolved lipid sensor by combining capillary electrophoresis separation in a PDMS microfluidic chip online with mid-infrared (MIR) absorption spectroscopy for biomarker detection. In this system, the detection platform is a PDMS microfluidic chip placed on top of a germanium substrate. On-chip capillary electrophoresis is used to separate the biomarkers without introducing any extrinsic contrast agent, which reduces both cost and complexity. The label free biomarker detection is done by interrogating separated biomarkers in the channel by MIR absorption spectroscopy. Phospholipids biomarkers of degenerative neurological, kidney, and bone diseases are detectable using this label free technique. These phospholipids exhibit strong absorption resonances in the MIR and are present in biofluids including urine, blood plasma, and cerebrospinal fluid. MIR spectroscopy of a 12-carbon chain phosphatidic acid (PA) (1,2-dilauroyl-sn-glycero-3-phosphate (sodium salt)) dissolved in N-methylformamide, exhibits a strong amide peak near wavenumber 1660 cm-1 (wavelength 6 μm), arising from the phosphate headgroup vibrations within a low-loss window of the solvent. PA has a similar structure to many important phospholipids molecules like phosphatidylcholine (PC), phosphatidylinositol (PI), phosphatidylethanolamine (PE), phosphatidylglycerol (PG), and phosphatidylserine (PS), making it an ideal molecule for initial proof-of-concept studies. In conclusions, we present a new detection platform that requires minimal sample preparation and is capable of identifying several biomarkers from the same sample, simultaneously.

9166-59, Session 2

Optical printing and injection of gold nanoparticles into living cells

Miao Li, Theobald Lohmüller, Jochen Feldmann, Ludwig-Maximilians-Univ. München (Germany)

The active delivery of nanoscopic objects to the surface or interior of living cells with light offers promising prospects for the development of novel molecular delivery strategies or intracellular biosensor applications.

Previous works in our group showed that the gold nanoparticles could be not only patterned on glass surface by laser [1], but also be optically pushed through the lipid membrane [2]. In this study, we show that single gold nanoparticles (80 nm) from solution can be optically captured and patterned on Chinese hamster ovary (CHO) cells by using a 532 nm cw laser beam under dark-field microscope. We furthermore demonstrate that the particles can be injected into the cell by focusing the laser on the printed particles on the cell surface. We find that a short exposure time (within one second) is sufficient to perforate the cell membrane and inject the particles into the cell. The cell viability and cytotoxicity during printing and injection are investigated to help explaining the mechanism of the cell-nanoparticle interaction.

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9166-61, Session 2

Advanced terahertz imaging and spectroscopy systems based on plasmonic terahertz optoelectronics *(Invited Paper)*

Mona Jarrahi, Univ. of California, Los Angeles (United States)

We present an overview of recent advances in plasmonic photoconductive terahertz sources and detectors, enabling higher performance terahertz imaging and spectroscopy systems. We show that the use of plasmonic contact electrodes in a photoconductive terahertz source and detector manipulates the spatial distribution of photocarriers in the device active area and enhances the number of photocarriers in nanoscale distances from the contact electrodes significantly, enabling efficient collection of the majority of carriers in a sub-picosecond time scale. It also allows increasing photoconductor active area without a considerable impact on device parasitics, boosting the maximum terahertz radiation power and detection sensitivity by preventing the carrier screening effect and thermal breakdown at high optical pump powers. We experimentally demonstrate that the use of plasmonic photoconductive terahertz sources and detectors in a terahertz imaging and spectroscopy system offers more than four orders of magnitude higher signal-to-noise ratio levels compared to existing terahertz imaging and spectroscopy systems. This significant performance enhancement could offer numerous opportunities for e.g., medical diagnostics, biological sensing, pharmaceutical quality control, and medical imaging.

9166-18, Session 3

Computational microscopy, sensing, and diagnostics *(Invited Paper)*

Aydogan Ozcan, Univ. of California, Los Angeles (United States)

My research focuses on the use of computation/algorithms to create new optical microscopy, sensing, and diagnostic techniques, significantly improving existing tools for probing micro- and nano-objects while also simplifying the designs of these analysis tools. In this presentation, I will introduce a new set of computational microscopes which use lens-free on-chip imaging to replace traditional lenses with holographic reconstruction algorithms. Basically, 3D images of specimens are reconstructed from their “shadows” providing considerably improved field-of-view (FOV) and depth-of-field, thus enabling large sample volumes to be rapidly imaged, even at nanoscale. These new computational microscopes routinely generate >1–2 billion pixels (giga-pixels), where even single viruses can be detected with a FOV that is >100 fold wider than other techniques. At the heart of this leapfrog performance lie self-assembled liquid nano-lenses that are computationally imaged on a chip. These self-assembled nano-lenses are stable for >1 hour at room temperature, and are composed of a biocompatible buffer that prevents nano-particle aggregation while also acting as a spatial “phase mask.” The field-of-view of these computational microscopes is equal to the active-area of the sensor-array, easily reaching, for example, >20 mm2 or >10 cm2 by employing state-of-the-art CMOS or CCD imaging chips, respectively.

In addition to this remarkable increase in throughput, another major benefit of this technology is that it lends itself to field-portable and cost-effective designs which easily integrate with smartphones to conduct giga-pixel tele-pathology and microscopy even in resource-poor and remote settings where traditional techniques are difficult to implement and sustain, thus opening the door to various telemedicine applications in global health. Some other examples of these smartphone-based biomedical tools that I will describe include imaging flow cytometers, immunochromatographic diagnostic test readers, bacteria/pathogen sensors, blood analyzers for complete blood count, and allergen detectors. Through the development of similar computational imagers, I will also report the discovery of new 3D swimming patterns observed in human and animal sperm. One of this newly discovered and extremely rare motion is in the form of “chiral ribbons” where the planar swings of the sperm head occur on an osculating plane creating in some cases a helical ribbon and in some others a twisted ribbon. Shedding light onto the statistics and biophysics of various micro-swimmers’ 3D motion, these results provide an important example of how biomedical imaging significantly benefits from emerging computational algorithms/theories, revolutionizing existing tools for observing various micro- and nano-scale phenomena in innovative, high-throughput, and yet cost-effective ways.

9166-19, Session 3

Electron optics of nanoplasmonic metamaterials in bio/opto theranostics *(Invited Paper)*

Donald K. Roper, Univ. of Arkansas (United States) and National Science Foundation (United States); Drew DeJarnette, Department of Mechanical Engineering, University of Tulsa (United States); Greg T Forcherio, Microelectronics-Photonics Graduate Program (United States); Jeremy Dunklin, Keith Berry Jr., Department of Chemical Engineering, University of Arkansas (United States); Gyoung Jang, Oak Ridge National Laboratory (United States); Milana Lisunova, Department of Chemical Engineering, University of Arkansas (United States); Phillip T Blake, Departments of Math and Science (United States); Wonmi Ahn, Department of Chemistry, Boston University (United States)

Opto-electronic coupling of plasmonic nano-antennas in the near infrared water window is of growing interest for biosensing, opto-theranostics, and drug delivery. Dynamic enhancement of opto-electronic coupling could advance synthetic biology and enhance neurotechnologies. Fundamentally, quantized photon-exciton coupling supports induced charge transfer in ordered DNA chains and distance-dependent Forster resonance energy transfer in spectroscopic molecular rulers.

Our lab distinguished contributions of quantized plasmon polarizabilities and photon diffraction to opto-electronic coupling in ordered metal-ceramic and polymeric nanocomposite metamaterials for bio/opto theranostic applications. Metamaterials exhibit tunable electromagnetic functionality (e.g., iridescence in butterfly wings; radiofrequency cloaking) due to coherent interference from multiscale structuring of nanocomposites. We have made rapid progress recently in self-assembling plasmonic metamaterials on ceramic and biocompatible polymeric substrates, and distinguishing coherent and incoherent optical re-radiation and thermal dissipation from plasmonic nano-antennas in biocompatible devices.

Design of dynamical electron optics in bioelectronic systems has been obstructed by computational expense and complexity. Our lab has developed and validated several approximations that integrate near-field polarizability and far-field modal interference to describe electron optic coupling in metamaterials and biodevices. This speeds design and description of new ring nanoarchitectures that show promise for bioapplications.

We characterize our fabricated metamaterials and validate their fundamental descriptions using microspectroscopies (x-ray photoelectron; transmission UV) and transmission/scanning electron and optical microscopies. Such analysis has supported measurable improvements in opto-electronic interactions in nano-scale metallic particles and films for bio/opto theranostics.

9166-20, Session 3

Improving the performance of silicon photonic rings, disks, and Bragg gratings for use in label-free biosensing

Shon A. Schmidt, Univ. of Washington (United States); Jonas Flueckiger, Department of Electrical and Computer Engineering, The University of British Columbia (Canada); WenXuan Wu, Department of Bioengineering, The University of Washington (United States); Samantha M Grist, Sahba Talebi Fard, Department of Electrical and Computer Engineering, The University of British Columbia (Canada); Valentina Donzella, Department of Electrical and Computer Engineering, The University of British Columbia, (Canada); Pakapreud Khumwan, Emily R Thompson, Qian Wang, Pavel Kulik, James T Kirk, Department of Bioengineering, The University of Washington (United States); Karen C Cheung, Lukas Chrostowski, Department of Electrical and Computer Engineering, The University of British Columbia (Canada); Daniel M Ratner, Department of Bioengineering, The University of Washington (United States)

Silicon photonics is emerging as a mainstream technology for high performance computing and telecommunications. As near-infrared light propagates through nano-scale silicon wires on a chip, a portion of the light travels outside the waveguide, sensitive to refractive index changes such as molecules binding on its surface. This feature makes silicon photonics an ideal platform for label-free biosensing and promises the advent of highly-matrixed medical diagnostic lab-on-chip systems at the economies of scale only offered by today's CMOS foundries. In this paper, we describe a myriad of TE- and TM-mode silicon photonic resonators specifically optimized for biosensing applications such as: cascaded micro-rings, micro-disks, and slab- and slot-waveguide Bragg gratings. We demonstrate their biosensing capability and compare their performance in terms of bulk sensitivity, Q, and detection limit. Specifically, we demonstrate the improved bulk sensitivity of TM-mode micro-ring and micro-disk sensors over their TE counterparts and the resulting impact on particle detection and size differentiation. We also report on sensitivity improvements achieved by suspending the resonant sensing portion of Bragg grating sensors, creating more overlap between the evanescent field and bulk media. Finally, the performance of each sensor is compared for the detection of biological analytes for future application in lab-on-a-chip systems.

9166-21, Session 3

Novel 3D plasmonic nano-electrodes for intracellular investigations and neural interfaces

Mario Malerba, Michele Dipalo, Alessandro Simi, Hayder Amin, Luca Berdondini, Francesco De Angelis, Istituto Italiano di Tecnologia (Italy)

We present a novel, advanced and robust approach for the fabrication of 3D high aspect-ratio hollow plasmonic nanoantennas [1].

This not only provides a new fabrication method, which may outdo current limits in many fields, but also introduces a new class of nanostructured devices, to be employed and studied in fundamental and multidisciplinary research fields.

In detail, we report on large-scale matrices of vertical plasmonic hollow nanoantennas, fabricated on different supports. Among its traits, a high electric field enhancement from the architectures' hotspots and a reproducible resonance tunability in a broad range of the spectrum. The 3D nature of the fabricated devices enables us to realize efficient broadband-enhancement plasmonic architectures, electrically connected to an active electronic circuit without affecting its plasmonic functioning. Additionally, the hollow nature of the antennas enables the fabrication of microfluidic devices for intracellular drug-delivery experiments. The outstanding mechanical properties (flexibility and resistance) at last allow us to use the structures as microelectrodes for intracellular recordings [2], porating the outer membrane and accessing the cytosol environment. By fabricating such architectures onto pre-built, commercially available C-MOS multielectrode array circuits (MEAs), it is thus possible to synergistically study and monitor with an unprecedented sensitivity and resolution complex biological systems, such as neuron networks, merging electrical recordings with optoplasmonic spectroscopy.

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[2] M. E. Spira and A. Hai, Nature Nanotechnology 8, 83–94 (2013).

9166-22, Session 3

The whispering gallery mode biosensor: label-free detection from virus to single protein *(Invited Paper)*

Stephen Holler, Fordham Univ. (United States); Venkata R. Dantham, Stephen Arnold, Polytechnic Institute of New York Univ. (United States); Vasily Kolchenko, New York City College of Technology (United States); David Keng, Polytechnic Institute of New York Univ. (United States); Brigid Mulroe, Milan Paspaley-Grbavac, Fordham Univ. (United States)

The presence of infection or disease may be elucidated through the detection of pathogenic agents or protein markers within the bodily fluids. Such nanobioparticles circulate throughout the body and may serve as an indicator of infection or the reemergence of disease. However, for efficacious treatment to be administered early identification is necessary which requires the ability to ultrasensitive trace species detection. The whispering gallery mode biosensor has developed over the years as a sensitive photonic platform for the label-free detection of trace quantities of biological material. It has been successfully applied to the detection of bacteria, virus and protein. Single virus sensing has been achieved through the integration of plasmonic nanoparticles with the whispering gallery mode sensor. We recently reported label-free single protein detection using this nanoplasmonic-photonic hybrid resonant microcavity. Plasmonic-enhanced resonant systems have proven effective at being highly sensitive and highly responsive to changes in their environment. The textured surface of the plasmonic nanoparticles considerably boosts local electric field in the vicinity of the plasmon resonance. This enhancement facilitates the detection of individual viruses and protein markers making possible the sensitive detection of pathogens (e.g., Human Papillomavirus) and important disease markers (e.g., Thyroglobulin). The enhanced detection capability was demonstrated using small protein molecules (BSA (66 kDa) and Tg (660 kDa)), which resulted in the observation of a larger (2.4x - 15x) response than expected from this smooth surface model and allows us to project the limit of detection of the whispering gallery mode sensor to be 5 kDa.

9166-23, Session 3

Innovative optic sensing concepts towards applications in biotechnology and medicine *(Invited Paper)*

Joerg Opitz, Thomas Härtling, Susan Derenko, Carola E. Gerich, Manuela Reitzig, Olaf Roeder, Fraunhofer IKTS-MD (Germany)

The Fraunhofer Institute for Ceramic Technologies and Systems, Branch Materials Diagnostics (IKTS-MD) covers also fields of biosensing and nanotechnology, from basic research towards applications. This talk will address three optically based methods for sensing.

Improving cancer diagnosis is one of the important challenges at this time. The precise differentiation between benign and malignant tissue is of utmost significance in oncology and oncologic surgery. A diagnostic system based on the analysis of the fractal dimension of time-resolved auto-fluorescence spectroscopy will be illustrated. The results of different multi-clinical studies on prostate and oral tissue will be shown.

Especially in the food and medical sector regulations concerning sterility are increasingly tightened. A promising alternative to low-temperature and dry sterilization of surfaces for sensitive packaging materials is the electron beam treatment. For this, a secure proof for sterilization process is required. However, there does not exist any non-destructive and in

situ method up to now. Our approach is to integrate a suitable marker material based on rare-earth-doped phosphors in the packaging material of the respective product. We present our recent investigations on time-resolved measurements of alterations in the temporal luminescence decay of upconversion phosphors induced by electron beam irradiation.

The monitoring of drinking and waste water quality and water based processes in the chemical industry requires a sensor technology with the capability of being integrated in the process and a distinguished reliability. For this a refractive index sensing with a CCD chip technology based on localized SPR sensing will be discussed.

9166-24, Session 3

A portable surface plasmon resonance biosensor capable of phase interrogation in a large dynamics range *(Invited Paper)*

How-Foo Chen, Hsin-Yuan Chuang, National Yang-Ming Univ. (Taiwan); Chih-Hang Chen, Yun-Hsiang Chang, National Yang-Ming Univ (Taiwan)

Biosensors utilizing surface plasmon resonance (SPR) for drug and antibody screening, clinical examination, food pollution detection, and life science research have received tremendous investigation due to their characteristics of label-free operation, real-time observation, and high sensitivity detection. However, most of the current devices are either bulky with descent sensitivity or compact but with very limited sensitivity. Thus, with the development of a point of care (POC) biosensor in mind, a polymer-molding prism with double parabolic surfaces is invented and developed to implement an ultra-compact SPR biosensor with extremely high sensitivity. The polymer molded free-form prism is cost effective and then disposable, thus cross contamination of biological samples can be avoided. Also because of the low-cost consumable light-coupling part, this biosensor can extend the applications of SPR biosensors from laboratory studies to clinical practices. A highly sensitive biosensor with a form factor less than 15cm*15cm*5cm was received with a tunable excitation angle of light beam for a large dynamic range. The invented optical structure can easily utilize optical phase interrogation, which usually requires a very precise optical alignment, with a tunable light incident angle. A 635nm laser beam and Au coating of around 47.5nm is used to test the sensitivity. Detection of limitation with the value of less than 5.0x10-7 refractive index unit was obtained. The device is also compatible to a modern microscopy platform.

9166-25, Session 3

Optofluidic cellular immunofunctional analysis by localized surface plasmon resonance *(Invited Paper)*

Katsuo Kurabayashi, Bo-Ram Oh, Univ. of Michigan (United States)

Biomolecular motors are nanometer-scale biomaterials that convert chemical energy stored in ATP into mechanical work. They are responsible for mass transport and cell movement in biological systems. The bionanotechnology research community has recently been exploring the development of new hybrid devices that incorporate biomolecular motors in a non-biological engineered material structure. Manipulation of nanomechanical structures using these motors is an excellent example of utilizing life's natural resources to power man-made systems at high fuel-to-power conversion efficiency. This talk discusses our research on nanometer-scale molecular sorting and biosensing utilizing biomolecular motor-integrated micro/nano materials and devices with a fundamental understanding of nanomechanical processes to control their stochastic movements. Expected advantages and technological challenges accompanying the hybrid devices are also discussed.

9166-26, Session 3

Elucidation of protein-small molecule interactions using a single particle aperture optical trap

Ryan M. Gelfand, Ahmed Al-Balushi, Abhay Kotnala, Skylar Wheaton, Reuven Gordon, Univ. of Victoria (Canada)

Current methods for characterizing protein-small molecule interactions are generally assay based and require a significant amount of preparation; for example, fluorescent labeling. By using a double nanohole optical aperture trap a single protein can be trapped and characterized both with and without the addition of a small molecule. These interactions are vital to understanding many drug molecule workings and may help drug discovery. The optical behavior of the trap changes depending on the geometric properties and dynamics of the protein being trapped and by changing these characteristics we can separate one interaction type from another. For example streptavidin and biotinylated streptavidin can be identified based on their respective effects on the optical properties of the transmitted light exiting the aperture trap. Furthermore using a microfluidic flow channel integrated with the double nanohole trap, real time studies of the bonding dynamics between these two analytes can be studied without steric hindrance of the protein. The trapping laser uses less power than conventional gradient force optical trapping, and heat is efficiently removed from the trapping region by the gold film. Therefore, this process is nondestructive, and because the wavelength used is in the near infrared non-resonant Raman studies may be performed in-situ. This technique can be made portable and compact by fabricating the trap onto the end of an optical fiber and multiplexed by bundling many of them together. This new construct would allow researchers to conduct experiments in parallel, being able to then extract large amounts of data quickly and efficiently.

9166-27, Session 4

Nanoscale fiber tip probe for biomedical sensing *(Invited Paper)*

Qimin Quan, Wooyoung Hong, Harvard Univ. (United States); Feng Liang, Diane Schaak, The Rowland Institute at Harvard (United States); Marko Loncar, Harvard School of Engineering and Applied Sciences (United States)

Rapid and sensitive biosensors are gaining increasing importance in biomedicine and public health. Fluorescence based assays (e.g. enzyme-linked immunosorbent assay (ELISA), microarray, green fluorescent protein) have enabled a number of scientific advances and commercial applications. However, the labeling approaches are often difficult to control and may interfere with receptor affinity. I will describe a label-free nanoscale fiber tip probe as a tool for in vitro protein detection. I will compare the sensitivity of the bioprobe with standard assays such as ELISA, and traditional SPR sensors, such as Biacore. Furthermore, I will discuss the application of the nanscale fiber tip probe to detect intracellular proteins.

The fiber tip probe has a 5 micrometer length and sub-100 nanometer-diameter. One single gold nanorod is attached to the end of the tip, and the surface of which was functionalized with antibodies specific to the target analyte. The collective oscillation of the conductive electrons in the gold nanorod couples strongly to polarized light in the visible wavelength range, generating a localized surface plasmon resonance (LSPR) signal, and is sensitive to small perturbations to its optical mode near its surface. Therefore, the fiber tip probe can be used as a bioprobe to detect proteins that are captured on the gold nanorod surface.

9166-28, Session 4

Portable optical sensors imaging systems for biomedical applications *(Invited Paper)*

Ofer Levi, Univ. of Toronto (Canada)

We present the development of miniature optical sensors inside micro-fluidic channels for biomedical diagnosis and molecular studies. We have developed a miniature GaAs-based fluorescence sensor including VCSELs, PIN diode and filters, packaged it with a low noise CMOS readout and demonstrated high sensing sensitivity and the ability to implant it in living mice. In addition, we have shown that using photonic crystal slab (PCS) nanostructures, parameters such as spectral sensitivity (nm/RIU) and quality factor for an index of refraction sensor can be optimized simultaneously, leading to limit of detection better than 10^-7 RIU and to sensing sensitivity >0.8 of the theoretical limit.

We present the development of a multi-modality optical neural imaging system, based on fast coherence reduction techniques applied to Vertical Cavity Surface Emitting Lasers (VCSELs) operating at 680, 795 and 850 nm. We demonstrate a novel system which combines the two techniques of laser speckle contrast imaging (LCSI) and intrinsic optical signal imaging (IOSI) simultaneously, using these compact laser sources, to monitor induced cortical ischemia in a full field format with high temporal acquisition rates. We will also present our initial design and system analysis for a low-cost CMOS-based portable imaging system as a minimally invasive method for long-term neurological studies in un-anesthetized animals. This system will provide a better understanding of the progression and treatment efficacy of various neurological disorders, in freely behaving animals.

9166-29, Session 4

Biologically inspired materials *(Invited Paper)*

Alon Gorodetsky, Univ. of California, Irvine (United States)

Cephalopods are known as the chameleons of the sea – they can alter their skin's coloration, patterning, and texture to blend into the surrounding environment. These capabilities are enabled by unique proteins and self-assembled nanostructures found within cephalopod skin. We will discuss our work on new types of photonic and ionic devices from naturally occurring materials found in cephalopods. Our findings hold implications for the next generation of camouflage and renewable energy technologies.

9166-30, Session 4

Nanocrystal optical sensors and multimodal optical imaging for quantitative nanomedicine *(Invited Paper)*

Jeeseong Hwang, National Institute of Standards and Technology (United States)

Quantitative detection and imaging of pathogens, infectious agents, and cancer plays a vital role in biological threat surveillance, agricultural safety, and medical diagnosis. While there is increasing interest in highly sensitive detection assays involving either fluorescent molecules or light-emitting chemical reactions, they often pose challenges to quantitative optical analysis. I will present our recent results on characterizing and modeling the unique optical properties of novel nanocrystal probes and quantitative imaging of molecular processes in cells and tissues. I will also present our ongoing efforts on developing novel hyperspectral multimodal imaging platforms and standards to apply nanocrystals and molecular sensors in several important biomedical applications. Such applications include visualizing dynamic characteristics of cells in a disease state and developing optical standards for effective and safe hyperthermia cancer treatments.

9166-31, Session 4

Silicon nano-photonic devices optimized for label-free biosensing applications *(Invited Paper)*

Lukas Chrostowski, The Univ. of British Columbia (Canada); Shon A. Schmidt, Univ. of Washington (United States); Jonas Flueckiger, Sahba Talebi Fard, The Univ. of British Columbia (Canada); Valentina Donzella, The Univ. of British Columbia (Italy); Samantha M. Grist, The Univ. of British Columbia (Canada); WenXuan Wu, Qian Wang, Pavel Kulik, James Kirk, Daniel Ratner, Univ. of Washington (United States)

Silicon photonics is emerging as a mainstream technology for high performance computing and telecommunications. As near-infrared light propagates through nano-scale silicon wires on a chip, a portion of the light travels outside the waveguide, sensitive to refractive index changes such as molecules binding on its surface. This feature makes silicon photonics an ideal platform for label-free biosensing and promises the advent of highly-matrixed medical diagnostic lab-on-chip systems at the economies of scale only offered by today's CMOS foundries. In this paper, we describe a myriad of TE- and TM-mode silicon photonic resonators specifically optimized for biosensing applications such as: cascaded micro-rings, micro-disks, and slab- and slot-waveguide Bragg gratings. We demonstrate their biosensing capability and compare their performance in terms of bulk sensitivity, Q, and detection limit. Specifically, we demonstrate the improved bulk sensitivity of TM-mode micro-ring and micro-disk sensors over their TE counterparts and the resulting impact on particle detection and size differentiation. We also report on sensitivity improvements achieved by suspending the resonant sensing portion of Bragg grating sensors, creating more overlap between the evanescent field and bulk media. Finally, the performance of each sensor is compared for the detection of biological analytes for future application in lab-on-a-chip systems.

9166-32, Session 4

Plasmonic nanosensors for molecular and functional cancer imaging and therapy *(Invited Paper)*

Konstantin V. Sokolov, The Univ. of Texas M.D. Anderson Cancer Ctr. (United States)

Gold made materials undergo fascinating changes in physicochemical properties when their size is reduced to nanoscale. This phenomenon has been observed as long as some thousands years ago with many famous examples such as the Roman Lycurgus cup from AD400 that makes nanotechnology an ancient filed of human endeavors. Nowadays, we are studying fundamental properties of gold nanoparticles and their interactions with biological environment with the ultimate goal to harness the nanoscale material properties for improved imaging and therapy of devastating diseases such as cancer.

In this talk, I will discuss three interconnected areas of research that are involved in development of plasmonic nanosensors for biomedical applications: (1) synthesis of biocompatible molecular specific gold nanoparticles; (2) studies of mechanisms of nanoparticle interactions with cells and tissues to enable molecular-specific imaging and therapy; and (3) optimization of nanoparticles for clinical translation.

9166-33, Session 4

Probing the nano-bio interface with nanoplasmonic optical probes *(Invited Paper)*

Xinwei Yu, Linxi Wu, Ali Khanehzar, Amin Feizpour, Fangda Xu, Björn M. Reinhard, Boston Univ. (United States)

Noble metal nanoparticles have large cross-sections in both optical and electron microscopy and plasmon coupling between noble metal nanoparticles facilitate the characterization of subdiffraction limit separations through spectral analysis of the scattered light in plasmon coupling microscopy. The size compatibility of noble metal nanoparticles together with the ability to encode specific functionality in a rational fashion by control of the nanoparticle surface makes noble metal nanoparticles unique probes for a broad range of biological processes. Recent applications of the technology include i.) characterization of cellular heterogeneity in nanomaterial uptake and processing through macrophages, ii.) testing the role of viral membrane lipids in mediating viral binding and trafficking, and iii.) characterizing the spatial organization of cancer biomarkers in plasma membranes. This paper reviews some of these applications and introduces the physical and material science principles underlying them. In particular, we will focus in this presentation on the use of membrane wrapped noble metal nanoparticles, which combine the superb photophysical properties of a nanoparticle core with the biological functionality of a membrane, as probes in Plasmon Coupling Microscopy (PCM).

9166-34, Session 4

A prism coupled light sheet microscope for single molecule super-resolution imaging *(Invited Paper)*

Hu Cang, The Salk Institute (United States)

A light sheet microscope, which selectively illuminates a thin plane of a sample with a sheet of light, offers extraordinary signal-to-noise ratio for tissue imaging. The current design of light-sheet microscopes is essentially unchanged since its invention in 1903. This design, which uses an orthogonal configuration of a condenser and an objective lens. has severe limitations on the numerical aperture (NA) of the objective lens that can be used for light sheet microscopy, and is unsuitable for single molecule detection. Here we present a new design of light sheet microscope, which use a prism to couple the light sheet into the sample. this new design relax the angle between the condenser and objective, which allows the use of high NA lens for single molecule imaging. We demonstrate its value by imaging chromatin of stem cells with nanometer scale resolution. In addition, we show that this prism coupled light sheet microscope is also compatible with a recently developed Bayesian microscopy for high-speed live cell imaging.

9166-35, Session PWed

Effect of amine functionalized polyethylene on clay-silver dispersion for polyethylene nanocomposites: mechanical and antimicrobial properties

Saul Sanchez, Centro de Investigacion en Quimica Aplicada (Mexico)

The compatibilization effects provided by Maleic anhydride (MA), Itaconic Acid (IAc), Itaconic anhydride (IA) and 2-[2-(dimethylamine)-ethoxy] ethanol (DMAE) functionalized polyethylenes for forming high density polyethylene-based nanocomposites were studied and compared. IAc, IA were grafted into HDPE by melt mixing to obtain functionalized polyethylenes (HDPEgIAc and HDPEgIA) and amino alcohol functionalized polyethylene was prepared by reaction of commercial HDPEgMA with DMAE in the melt to form polyethylene grafted dimethyl amine ethoxy ethanol (PEgDMAE). Nanocomposites were prepared by melt processing using a twin screw extruder by blending polyethylene and these compatibilizers, with a quaternary ammonium surfactant modified montmorillonite clay (Nanomer I28E) impregnated with silver nanoparticles. FTIR characterization confirmed the formation of these compatibilizers and confirmed the reaction between HDPEgMA and the amino alcohol. All the compatibilized nanocomposites had better clay exfoliation and silver dipersion compared to the uncompatibilized HDPE nanocomposites. Mechanical and barrier properties, X-Ray diffraction, thermo gravimetric analysis and transmission electron microscopy results, as well as antimicrobial behviour against a bacteria (E.Colli) and a fungus (A. Nigger) showed the next order in their decreasing performance behaviour as compatibilizer: PEgDMAE>HDPEgAI>HDPEgAcI>HDPEgMA. This behavior was attributed to the specific interactions between the anionic surface of the clay and the functionality of the compatibilizer. Samples with higher clay content showed poor clay dispersion or intercalation which was attributed to a possible clay saturation when the van der Waals attractive interactions between clay layers becomes dominant when the distance between them is smaller at a certain concentration of clay.It was demonstrated the synergistic effect of both clay and silver nanoparticles on antimicrobial properties of the nanocomposite. Possible interaction between compatibilizer and nanoparticles was schematized.

9166-36, Session PWed

Generation of reactive oxygen species from 5-aminolevulinic acid and glutamate in cooperation with excited CdSe/ZnS QDs

Hong Dinh Duong, Jee Won Lee, Jong Il Rhee, Chonnam National Univ. (Korea, Republic of)

CdSe/ZnS QDs can be joined in the reductive pathway involving the electron transferring to an acceptor or in the oxidative pathway involving the hole transferring to a donor. They were exploited in the oxidation reactions of 5-aminolevulinic acid (ALA) and glutamate (GLU) for the generation of reactive oxygen species (ROS) such as hydroxyl radical (HO•) and superoxide anion (O2••). The fast and highly efficient oxidation reactions of ALA to produce the HO• and in case of GLU to produce the O2•• were observed in the cooperation of mercaptopropionic acid (MPA) capped-CdSe/ZnS QDs. Fluorescence spectroscopy and Electron Spin Resonance (ESR) spectroscopy were used to evaluate the generation of different forms of ROS. Effect of the generated ROS on HeLa cells was real time monitored.

9166-37, Session PWed

Enhancement of singlet oxygen production based on FRET between Coumarin tri-compound and CdSe/ZnS QDs

Hong Dinh Duong, Jee Won Lee, Jong Il Rhee, Chonnam National Univ. (Korea, Republic of)

In this work, CdSe/ZnS QDs were synthesized and then exchanged ligands on their surface by using mercaptopropionic acid (MPA) to produce water-soluble QDs (MPA-QDs). The silica particles-captured coumarin tri-compound (SiC3) were also synthesized as a source of energy transfer for MPA-QDs. Based on FRET from SiC3 to MPA-QDs, the singlet oxygen production from MPA-QDs was significantly enhanced (80%) as compared with that of MPA-QDs without SiC3. Sol-gel of 3-glycidoxypropyl trimethoxysilane (GPTMS), 3-aminopropyltrimethoxysilane (APTMS) was used as the linking between SiC3 and QDs and produced an effective combination and stability in reaction of singlet oxygen production. Effect of the generated ROS on animal cells was real time monitored.

9166-38, Session PWed

Chemical sensors of biopolymers and hydrogen-containing components on the basis of nanodimensional porous Si

Liubomyr S. Monastyrsky, Ivan Franko National Univ. of L'viv (Ukraine)

The research is aimed at the development of nanoelectronic devices such as biosensors and molecular transmitters which are formed by integration of biological materials with micro-and nanoelectronic devices. It is presented spectral sensitivity of porous silicon (PC) to covering and status of biocomponent coatings, such as proteins (interferon, chicken egg protein), hygrogen-containing environment (methane, hydrogen, ammonia, ethanol).

Sensory properties of heterostructures (HS) were studied using the methods of luminescence, thermostimulated depolarization (TSD) and impedance measurements.

We have found changes in the PL spectra of the HS in the visible spectrum and in the spectra of TSD at excitation by nitrogen laser. Comparison of PL spectra of PC and HS of biopolymer (interferon)- PC indicates the quenching of PL maximum intensity, its displacement by 50 nm to 600 nm and the emergence of a new PL band in the vicinity of 500 nm. The dependences of conductivity and capacitance of PC–hydrogen-containing environment HS on the pressure of methane, hydrogen, ammonia and ethanol were obtained. It has been shown that the studied HS are also promising for quality control of food (eg, changes in the luminescence spectra of PS chicken protein HS depending on the quality of the product), for monitoring the environment on content and concentration of some gases (H2, CH4, NH3, C2H5OH) and can be suitable for fabrication of optical (fluorescent) and electro-sensors based on nanostructured por-Si.

9166-39, Session PWed

Multivariate system of orientational tomography of biological crystals birefringence networks

Natalia I. Zabolotna, Vinnytsia National Technical Univ. (Ukraine); Alexander G. Ushenko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

This work contain the data about methodological algorithm of usage Mueller-matrix tomography in investigation of optically – anisotropic layers. Presented the theoretical algorithms unleashing direct and inverse problems of diagnostics and presentation of anisotropy distribution of biological networks.

Described the system of Mueller-matrix tomography, which contains methods of oriental tomography. Proposed the experimental method of oriental tomography of polycrystalline protein networks of optically-thin layer in biological tissues, which contains from next parts:

• Distribution of optically-thin layer of biological tissues in optical disposition of polarimeter.

• Forming polarization rendering conditions of determined directions of optical axis in polycrystalline network.

• Detecting in CCD-camera plane series of microscopical polarization-filtered images.

• Determination statistical, correlational and spectral moments, which characterize distribution of optical axis direction, autocorrelation functions and spectrums of capacity such distributions.

9166-40, Session PWed

System of the phase tomography of optically anisotropic polycrystalline films of biological fluids

Natalia I. Zabolotna, Vinnytsia National Technical Univ. (Ukraine); Alexander G. Ushenko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine); Artem O. Karachevtsev, Yuriy Fedkovych Chernivtsi National Univ (Ukraine)

The article highlights the theoretical algorithms to solve direct and inverse problems of diagnosis and for reproducing distribution of the anisotropy parameters of polycrystalline networks of the biological environments.

It describes the system of complex Mueller-matrix tomography, including methods of the phase tomography.

It is proposed an experimental method of the phase tomography of polycrystalline protein networks of the optical thin layers of biological tissues. The method includes the following stages:

• Placing optical thin layer of biological tissue in the optical polarimeter scheme.

• Creating conditions for polarizing phase visualization of the polycrystalline birefringence optical network.

• Registering the camera of polarizing filtered images in the CCD plane

9166-41, Session PWed

Laser system of the autofluorescence polarimetry of cytologic layers at an early stage of cancer detection

Yuriy A. Ushenko, Maxim Sidor, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

This article presents the research results of the laser polarization fluorescence of biological layers (histological sections, cytological smears). It highlights the discovered and investigated polarized structure of the autofluorescent image layers of biological tissues and fluids. It is proposed a model describing the formation of polarizing inhomogeneous autofluorescence images of the optical biological optically anisotropic layers. Basing on this, the method of laser autofluorescence polarimetry was analytically grounded and experimentally tested. Its efficiency lies in the detection and differentiation of the uterine wall cancer (dysplasia - microinvasive cancer) at an early stage. There were defined the objective criteria (statistical moments) of differentiation of autofluorescent images of the endometrial biopsy histological sections and cytology samples of its mucous. The operational characteristics of this technique (sensitivity, specificity, accuracy) were determined.

9166-42, Session PWed

Fluorescent biopsy of biological tissues in differentiation of benign and malignant tumors of prostate

Yuriy A. Ushenko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

This paper presents the results of investigation of laser polarization fluorescence of biological layers. Detected and investigated polarization structure of autofluorescent images of human biological tissues and fluids. Proposed the model of description of polarization- heterogeneous images of optically anisotropic biological layers. On this basis analytically founded and experimentally checked the method of autofluorescent polarization-variability. Analyzed efficiency of application in the different tasks of medical diagnostics: detection and differentiation early cancer forms (dysplasia - microinvasive carcinoma) of uterine neck. The objective criteria (statistical moments) of differentiation of autofluorescent images of histological sections, endometrium and cytologic films of mucosal tunic were defined. The operational characteristics (sensitivity, specificity, accuracy) of this technique were determined concerning the positions of probative medicine, and clinical efficiency of the technique was demonstrated.

9166-43, Session PWed

Statistical and fractal analysis of autofluorescent myocardium images in posthumous diagnostics of acute coronary insufficiency

Taras M. Boychuk, Bukovinian State Medical Univ. (Ukraine)

This research presents the results of investigation of laser polarization fluorescence of biological layers (histologic section). Detected and investigated the polarizational structural properties of autofluorescence images of human biological tissues. Analytically founded and experimentally checked the method of autofluorescent polarization-variability. Analyzed the efficiency of application this method in criminal anthropology rapid differentiation reasons of death coming. The objective criteria (statistical moments) of differentiation of autofluorescent images of histological sections of myocardium biopsy, endometry and cytology of mucous were defined. The operational characteristics (sensitivity, specificity, accuracy) of these technique were determined concerning the positions of probative medicine, and clinical efficiency of the technique was demonstrated.

9166-44, Session PWed

Polarization-correlation analysis of maps of optical anisotropy biological layers

Olexander V. Dubolazov, Yuriy A. Ushenko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

The theoretical background of azimuthally stable method of the Jones-matrix mapping of histological sections of biopsy of uterine neck on the basis of spatial-frequency selection of the mechanisms of linear and circular birefringence is presented.

It is analytically justified the use of new diagnostic correlation parameter - complex degree of mutual anisotropy (CDMA). The technique of measuring the coordinate distributions CDMA followed by space-frequency filtering of the high-and low-frequency components.

It is found the interaction of such distributions with parameters of the linear and circular birefringence gistologichenskih slices of endometrial uterine wall.

The comparative results of measuring the coordinate distributions of complex degree of mutual anisotropy formed by fibrillar networks of myosin and collagen fibrils of uterine neck tissue of different pathological states – pre-cancer (dysplasia) and cancer (adenocarcinoma) are shown.

The values and ranges of change of the statistical (moments of the 1st – 4th order) parameters of complex degree of mutual anisotropy coordinate distributions are studied. The objective criteria of diagnostics of the pathology and differentiation of its severity degree are determined.

9166-45, Session PWed

Proton-dependent multi-drugs release using CD44 targeted nanoparticles for the induction of biliary cancer cell death

Ilkoo Noh, Jihye Choi, Hyun-Ouk Kim, Yonsei Univ. (Korea, Republic of); Jin-Suck Suh, Yong-Min Huh, Yonsei Univ. College of Medicine (Korea, Republic of); Seungjoo Haam, Yonsei Univ. (Korea, Republic of)

Multi-drugs delivery, which is focused by different signaling pathways in cancer cell, can generate synergistic effect onto anti-proliferation of cancers. To enhance delivery efficiency with minimal side effect, we developed CD44 targeted multi-drugs nanoparticle (MDNPs) consisting of paclitaxel conjugated poly-L-lysine (PLL-PTX) and gemcitabine conjugated hyaluronic acid (HA-GEM). Paclitaxel, a fraction of PLL-PTX, contributes to hydrophobic interaction during particle formation and exhibit a slightly positive charge. Negatively charged HA, a fraction of HA-GEM, can induce CD44 receptor-mediated endocytosis. Therefore, MDNPs were formed by electrostatic interaction using complementary charge of dual polymers showing advantageous features of not only maintaining similar pharmacokinetic drug efficacy but also accelerating drug release at acidic endosome environment (pH=5.5) in cancer cells. As a proof of concept, we confirmed successful synthesis of PLL-PTX and HA-GEM by NMR and IR spectroscopy, and the formation of MDNPs were analyzed by AFM, DLS and zeta potential. In vitro CD44 specific uptake was analyzed by CLSM using rhodamine B conjugated MDNCs. In vitro cell viability and gene expression of MDNPs showed that they exhibited more inhibition of cell proliferation in CD44 positive cell lines (Hucct-1) than CD44 negative cell lines (SCK) and higher expression of Bax/Bcl-xL in Hucct-t than SCK. Consequently, these results demonstrate that multi-drugs conjugated MDNPs could achieve a synergistic effect and effective cellular uptake at targeted cancer cells compared to free drug.

9166-46, Session PWed

Optical pre-clinical diagnostics of the cervical tissues malignant changing

Sergey B. Yermolenko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine); Dmytro Voloshynskyi, Olexander Fedoruk, Bukovinian State Medical University (Ukraine); Ion Gruia, University of Bucharest (Romania); Dmitry Zimnyakov, Yury Gagarin State Technical University (Russian Federation)

This work is directed to the investigation of the scope of the technique of laser polarimetry of oncological changes of the human prostate and cervical tissues under the conditions of multiple scattering, which presents a more general and real experimental clinical situation.

To compare the above mentioned scope of biotissue laser polarimetry on the first stage the research of human prostate and cervical tissues in the conditions of single scattering was performed.

Analytical approach to the analysis of polarizationally inhomogeneous images of human prostate tissue is based on the main model theses of laser polarimetry technique, according to which biological tissue (BT) is treated as a monolayer containing the ensemble of optically uniaxial birefringent fibrils.

Statistic moments of the first (M), second ( ), third (A) and fourth (E) orders were used as the analytical tool for estimating the ensemble of random values of z, that characterize the image of biological object (intensity I, polarization azimuths and ellipticities) and its optical-geometrical structure (orientation directions of the protein fibrils and birefringence index of their substance).

It was shown that the difference between the values of average and dispersion of distributions I (0 - 0), I (0 - 90), the intensities of images of various types of prostate tissues are insufficient and are within 10%-25%. The values of the excess of intensity distribution of the images of oncologically changed prostate tissues differ from the similar parameter of a sound tissue by 1-2 times. The third statistic moment proved to be the most sensitive to pathological changes in orientation structure. Its value in the intensity distribution of polarization image I (0 - 90) of oncologically changed tissue is 21 times higher if compared with the similar statistic parameter of the intensity distribution of the healthy tissue.

9166-47, Session PWed

Diagnostic value spectropolarimetry of blood plazma in patients with breast cancer

Alexander G. Prydiy, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine); Tetjana Kruk, Bukovinian State Medical University

(Ukraine); Pavlo Ivashko, Yuriy Fedkovych Chernivtsi National Univ (Ukraine); Olga Ushakova, Yury Gagarin State Technical University (Russian Federation)

The aim was to study the possibility of using polarimetry methods of performance evaluation of blood plasma of patients with breast cancer and spectroscopy method in the diagnosis of breast cancer and determine the criteria for their use of non-invasive screening for problems.

This paper presents the results of a comprehensive survey of 101 breast cancer patients aged 27 to 75 years who were hospitalized in Chernivtsi clinical oncology clinic. The paper also used 101 primary surgical specimens of patients with breast cancer. All patients were comprehensive survey of the use of common clinical practices according to the standards of diagnosis and treatment of patients with malignant tumors, adopted in Ukraine. Patients underwent radical surgery. They did not receive neoadjuvant chemotherapy, hormone and radiation therapy. All patients agreed to participate in the study. The control group consisted of 50 patients.

Laser image of inhomogeneous polarization component plasma is a polycrystalline network formed by ensembles excoptically uniaxial crystals albumin and globulin. Depending on the availability of cancer spatial orientation the structure of the network undergoes the following changes :

- blood plasma of healthy women is characterized by the predominance of large-scale, organized in the areas of optical axes of the crystals albumin SSC disordered in the fields of optical axes crystals globulin;

- laser images of human plasma, patients with breast cancer, we noticed the trend - the predominance of small-scale networks disordered crystals globulin;

- polarization properties of polycrystalline chains of amino acids in blood plasma can be defined as a single polycrystal properties and describes a set of static points in the 1st - 4th order and logarithmic dependencies of power spectra of coordinate distributions of the elements of the generalized Mueller- matrix operator.

It is shown that algorithms of statistical analysis, correlation and fractal analysis approaches Mueller-matrix and polarization images of crystalline layers of blood plasma can used as diagnostic methods for patients with breast cancer,

Absorption bands of vibrational transmission spectra of blood plasma of patients of group 1 - 3 were identified; most difference in the behavior of the absorption spectrum manifested in the region 1400- 2900 cm- 1 in patients of group 3.

9166-48, Session PWed

Absorption spectra of adenocarcinoma and squamous cell carcinoma cervical tissues

Pavlo V. Ivashko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine); Olexander Peresunko, Natalia Zelinska, Bukovinian State Medical University (Ukraine); Marina Alonova, Saratov State Technical University (Russian Federation)

We studied a methods of assessment of a connective tissue of cervix in terms of specific volume of fibrous component and an optical density of staining of connective tissue fibers in the stroma of squamous cancer and cervix adenocarcinoma. An absorption spectra of blood plasma of the patients suffering from squamous cancer and cervix adenocarcinoma both before the surgery and in postsurgical periods were obtained. Linear dichroism measurements transmittance in polarized light at different orientations of the polarization plane relative to the direction of the dominant orientation in the structure of the sample of biotissues of stroma of squamous cancer and cervix adenocarcinoma were carried.

In this study, first used methods of assessment of the connective tissue of the cervix in terms of specific volume of fibrous component and the optical density of staining of connective tissue fibers in the stroma of squamous (keratinizing and nonkeratinizing) cancer (n = 25) and adenocarcinoma of the cervix (n = 19). These results likely allow precise histochemical differential diagnosis of squamous and glandular cancers of different stages of differentiation (G1, G2, G3), indicating the feasibility of using computer microspectrophotometry in terms of additional sensitive diagnostic test .

Studies suggest that there are dependencies between pathological conditions of cervical stroma and performance that takes into account these data to compile prognosis of adenocarcinoma or squamous cell carcinoma. Computer histochemical assessment of connective tissue fibers in nonkeratinizing squamous cell carcinoma and adenocarcinoma of the cervix and is sensitive additional differential diagnostic test that helps objectification assessment of histological preparations and opens new perspectives in the study of the mechanisms and patterns of development of malignancy tumors. It is researched that in all the cases the linear dichroism appears in biotissues with the cancer disease the magnitude of which depends on the type of the tissue and on the time of the cancer process development. The phenomenon of the linear dichroism formation has a selective character: maximum values Δ are observed in the area λ=410 – 430 nm and in the area λ= 500 – 530 nm; for the wavelenth λ< 300 nm and λ> 750 nm Δ is almost zero or zero.

As the linear dichroism is lacking for healthy tissues, then the obtained results can have diagnostic values with the purpose of detection and estimation of the stage of the cancer disease development.

9166-49, Session PWed

Dynamics of blood plazma by spectropolarimetry and biochemical techniques

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Oxygen, indispensable element of life is very active and toxic by its metabolites. They first action initiates a chain reaction of oxidative degradation of lipids and protein constituents of cell membranes. Lipid and protein peroxidation reactions have direct implications for membrane signaling mechanisms, affectingthe intercellular adhesion, receptors, antibodies, antigens expression. These mechanisms can be considered precursors of malignant transformation.

Early detection of such changes may be useful for early diagnosis for clinicians but also to establish an optimal molecular targeted therapy.

The aim of this paper is the identification of these changes by spectropolarimetry techniques, and completion of results by biochemical techniques.

This has been performed in cell membranes isolated by repeated ultracentrifugation from experimental tumors in their growth dynamics compared to normal tissue membranes. Recorded optical results were compared with quantitative measurements of lipid and protein peroxidation reaction performed on the same biological samples.

These were monitored by quantifying the concentration of MDA (malondialdehyde), being the degradation product of lipid peroxidation and total-SH groups (thiol) as a measure of protein oxidative attack.

The results indicate that the primary source of the attackare the lipid molecules, and only after the initiation of chain reactions and quantitative production of reactive oxygen species will be attack the proteins, while the natural defense systems (endogenous antioxidants) are activated.

Optical measurements are consistent with the biochemical anisotropy measured wavelengths correspond breaks overhead associated protein and lipid oxidative damage.

9166-51, Session PWed

Light-scattering properties of bacteria Desulfuromonas acetoxidans under the influence of nano silver particles

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Concentration changes and relative content of bacterial cells of D.acetoxidans in the intervals of sizes 0,2 - 2,0 μm under the influence of nano silver particles have been investigated. Correlation between these changes of light-scattering properties of bacterial cells and growth abilities of bacteria D. acetoxidans under inflence of silver nanoparticles and ions has been shown. The intensity of processes the peroxide oxidize of lipids and change of indexes of the antioxidant system the cells of D.acetoxidans at influence of silver nanoparticles and silver nitrate was the aim with work. A bacteria D.acetoxidans are obligative anaerobic sulfur bacteria of the aquatic sedimental environments that are able to Fe^{3+} dissimilative reduction and Ag^{1+} is able to renew to Ag^0. The influence of various concentrations of ferric (III) citrate, silver nanoparticles and silver nitrate on enzymatic activity of catalase and reduced glutathione synthesis by D. acetoxidans cells under their cultivation with fumarate addition and with absence of sulphur has been determined. Specific catalase activity increased with enhancing of ferric (III) citrate concentration and duration of bacterial cultivation under the addition of this salt. The highest specific catalase activity was determined on the second day of bacterial growth under the influence of all concentration range of investigated metal salt. The reduced glutathione content under silver nitrate and silver nanoparticles exposure varied depending on the cultivation time and metal concentration. The maximum reduced glutathione content has been observed. The mechanism of action the silver on bacterial D.acetoxidans cells has been description.

9166-52, Session PWed

Synthesis and characterization of fluorene-based NIR fluorescent dyes for in-vivo imaging

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Near-infrared (NIR) fluorescent organic dyes have emerged as in vivo fluorescence imaging agents due to deep tissue penetration, less photodamage and low autofluorescence by biomolecules. Here, we designed new water-soluble pi-conjugated NIR fluorescent dyes, which is relatively photo-stable with compared to the double bond-containing cyanine dyes. To obtain the NIR fluorescence signal, three types of fluorene-based donor-acceptor-donor (DAD) fluorescent dyes (Q-FITBTTFI, Q-FIBBTFI and Q-FITBBTTFI) have been designed and synthesized with fluorene as an electron-donating group, and 2,1,3-benzothiadiazole and benzo[1,2-c:4,5-c']bis[1,2,5]thiadiazole moieties as an electron-accepting group. The dyes exhibited relatively low fluorescence quantum yields with a broad fluorescence spectrum and large stoke-shift in water, as compared to commercially available dyes. Polymer vesicles and polymer nanoparticles (Pdots) containing the DAD fluorescent dyes were synthesized to improve the quantum yield and biocompatibility, etc. Among the new dyes presented herein, the vesicle of Q-FITBTTFI displayed the best fluorescence imaging in biological media and in-vivo imaging.

9166-53, Session PWed

Cationic water-soluble fluorescent probe with 15 crown-5 for potassium ion detection

Hyejin Choi, Bao-Lam Nguyen, Van Sang Le, Han Young Woo, Pusan National Univ. (Korea, Republic of)

We report a highly selective and sensitive potassium detection by cationic water-soluble fluorescent probe. New water-soluble fluorescent probes with a donor-π-acceptor structure based on 1,4-bis(styryl)benzene were synthesized with the 15-crown-5 group for selective binding for K^+ ions. This structure allows efficient intramolecular charge transfer (ICT) in the main backbone from donor to acceptor. In the presence of K^+ ions, the ICT interaction is possibly modulated due to the binding of potassium ions onto the crown ether, resulting in the changes in the fluorescence signal of the probe. The detection limit of potassium was measured to be ~ 1.15 nM.

9166-54, Session PWed

Graphene/ruthenium nanoparticles as tool for sensor development

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Biosensors can be applied in various samples including body fluids and environmental samples. We used innovative Screen-Printed Graphene Electrodes (SPGPHEs), because of its high surface area, thermal and electric conductivity. The electrodes were modified with nanoparticles to improve the electrocatalytic properties toward β-Nicotinamide (NADH) oxidation, so that it can be used for electrochemical biosensor device. We prepared triangular ruthenium nanoparticles using hydrothermal synthesis method. First, the electrode surface was covered with a film by electropolimerisation with o-Phenylenediamine onto graphene (SPGPHE/PoPD). Secondly, the SPGPHE/PoPD was modified with RuNPs, SPGPH/PoPD/RuNPs. Cyclic voltammograms of NADH on bare SPGPHE and SPGPH/PoPD/RuNPs modified electrode show that the electrocatalytic current decreased significantly (30%) when the RuNPs were absent from the electrode surface. A remarkable catalytic oxidation current at the modified electrode occurred at ca. 0V, which negatively shifted higher than 400 mV, compared with that at bare SPGPHE (ca. 450 mV). Our results demonstrated that the SPGPH/PoPD/RuNPs maintained a good electrochemical activity toward NADH and could be applied to the field for electrochemical sensors.

9166-55, Session PWed

Optimization of synthesis of nanosilica fillers for experimental dental nanocomposites

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The aim of this study was to Optimization of synthesise nanosilica fillers for use in the fabrication of experimental dental nanocomposites. Monodispersed, spherical silica nanoparticles were synthesised via a sol-gel process, and different size range of 20-100 nm was obtained. Surface treatment of the nanosilica was carried out with the silane coupling agent y-methacryloxypropyltrimethoxysilane (MPS) to reduce agglomeration of nanosilica. Experimental dental nanocomposites with two different filler contents, 30 and 35 wt%, were fabricated and polymerised with different light curing unit. The surface morphology, surface roughness, flexural strength and elastic modulus were evaluated and compared. A nanocomposite with 35% filler content showed higher filler compaction, lower surface roughness and higher elastic modulus than a nanocomposite filled with 30% filler. However, the nanocomposite in size of 30 nm and light curing of 40 s filled with 30% filler content

showed higher flexural strength. Based on the results obtained, the synthesised nanosilica is a promising material for the fabrication of dental nanocomposites for tooth-filling applications.

9166-56, Session PWed

A high-sensitivity ellipsometric biosensor under a liquid immersion micro flow paths environment

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Binding kinetics of peptides with immobilized antibody are investigated by ellipsometric biosensor under a liquid immersion environment on silicon substrate. In this work, the experimental setup for ellipsometric biosensor is based on custom-built rotating analyzer ellipsometer which is equipped with a micro flow path on silicon substrate. In conventional surface plasmon resonance sensor, it is difficult to distinguish between a change in the reflective index of the buffer solution and pure binding characteristics, and the changes in the reflective index of the buffer solution can always serve as measurement error factors. This ellipsometric biosensor was insensitive to the changes in the refractive index of the buffer solution, but it showed high sensitivity to the film thickness in p-wave anti-reflective boundary conditions. Accordingly, the binding and dissociation kinetics inherent in only the samples can be accurately measured almost without the influence of a change in the refractive index resulting from a buffer solution. In order to directly monitor the interaction of small molecule-protein, it is necessary to design a high-sensitivity biosensor with a sensitivity of greater than 1 pg/mm2. In this paper, we demonstrate how an ellipsometric biosensor based on silicon wafer in the p-wave anti-reflective condition can be used to directly obtain the interactions and binding kinetics of peptides with immobilized antibodies. We achieved a detection limit of 1.0 x 10-7 RIU, which is equivalent to 0.1 pg/mm2. This method is applicable not only to sensor applications, such as affinity biosensors, but also to highly sensitive kinetics for drug discovery.

9166-57, Session PWed

Self-assembled clusters of gold nanoparticles for cancer-targeted photothermal therapy

Mi Hwa Oh, Insu Kim, Jeong Heon Yu, Shinyoung Choi, Yoon Sung Nam, KAIST (Korea, Republic of)

We construct genetically programmed T7 bacteriophages (also called phages) as a hybrid nanoplatform to assemble gold nanoparticles (AuNPs) for cancer-targeted bio-imaging and photothermal therapy. To assemble AuNPs on the surface of T7 phages, a Au-binding peptide (MHGKTQATSGTIQS) is displayed on each gp10B capsid protein along with a PC3 human prostate cancer cell surface-binding peptide (IAGLATPGWSHWLAL) in a tandem sequence. We investigate if pre-synthesized AuNPs with a diameter of 5 nm can bind to the recombinant T7 phages, forming a AuNP-clustered hybrid nanostructure, while the cancer-targeting peptide still maintains its specific binding affinity toward target cancer cells. The prepared T7-templated clusters of AuNPs show targeted tumor detection on a dark-field microscope, which is a fast and sensitive tool without staining. In addition, they show a potential as an agent for photothermal therapy originated from gold plasmonics when illuminated by a visible light source with target specificity. We expect that Au-PC3-T7 phages can be widely applied as a multifunctional therapeutic system in the field of biomedical therapeutics.

9166-60, Session PWed

Synthesis of eco-friendly silver nanoparticles using plant extracts and assessment of their antimicrobial activity

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Increasing interest for the biosynthesis of metal nanoparticles is under investigation due to their wide biomedical applications and research interest in nanotechnology. Mentha asiatica and Ocimum basilicum leaves extracts were used to evaluate their extra cellular potential synthesis of silver nanoparticles and their bactericidal impact on different kinds of pathogenic bacteria. UV-Visible spectroscopy was utilized to monitor the formation of silver nanoparticles. XRD analysis of the formed silver nanoparticles revealed spherical and cubical shapes structure with different planes ranged between 111 to 311 planes. Scanning electron microscopy (SEM) was used to characterize the morphology of the nanoparticles obtained from plant extracts. The synthesized nanoparticles were found to be active against clinically isolated human pathogens, Staphylococcus aureus and Escherichia coli. Our work proffers an eco-friendly method for biogenic silver nanoparticles production. This could provide a faster synthesis rate comparable to those of chemical methods and potentially be used in areas such as food and medical applications.

9167-1, Session 1a

Spin-lasers: from optical gain to high-frequency operation *(Invited Paper)*

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Spin-lasers provide intriguing opportunities for room-temperature spintronic applications, not limited to magnetoresistance. Starting from optical selection rules, we describe desirable properties of semiconductor nanostructures which also enable improving the optical gain, responsible for stimulated emission. We explore the relation between electronic structure of the active region and the operation of spin-lasers that could lead to an improved operation in both static and dynamic properties, as compared to conventional lasers.

9167-2, Session 1a

Polarization dynamics in spin-polarized vertical-cavity surface-emitting lasers *(Invited Paper)*

Nils C. Gerhardt, Henning Höpfner, Markus Lindemann, Martin R. Hofmann, Ruhr-Univ. Bochum (Germany)

Spin-polarized lasers and especially spin-polarized vertical-cavity surface-emitting lasers (spin-VCSELs) are attractive novel spintronic devices providing functionalities and characteristics superior to their conventional purely charge-based counterparts. This applies in particular to ultrafast dynamics, modulation capability and chirp control of directly modulated lasers. Here we demonstrate that ultrafast oscillations of the circular polarization degree can be generated in VCSELs by pulsed spin injection which have the potential to reach frequencies beyond 100 GHz. These oscillations are due to the coupling of the carrier-spin-photon system via the optical birefringence for the linearly polarized laser modes in the micro-cavity and are principally decoupled from conventional relaxation oscillations of the carrier-photon system. Utilizing these polarization oscillations is a very promising path to ultrafast directly modulated spin-VCSELs in the near future as long as an effective concept can be developed to modulate or switch these polarization oscillations. After briefly reviewing the state of research in the emerging field of spin-VCSELs, we present a novel concept for controlled switching of polarization oscillations by use of multiple optical spin injection pulses. Depending of the amplitude and phase conditions of the excitation pulses, constructive or destructive interference of polarization oscillations leads to an excitation, stabilization or switch-off of these oscillations. Furthermore even short single polarization bursts can be generated with pulse width only limited by the resonance frequency of the polarization oscillation resonance frequency. Consequently, this concept is an important building block for using spin controlled polarization oscillations for future communication applications.

9167-3, Session 1a

Control of light polarization using spin-injected opto-electronic devices with vertical geometries *(Invited Paper)*

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In the past decade, a continous interest and a research effort have been dedicated to the study of spin injection into Semiconductor-based Light Emitting Device such as Spin-Light Emitting Diodes (Spin-LEDs) [1,2] and more recently Spin-LASERs such as Vertical Cavity Surface Emitting LASERs (VCSELs) [3].

We will first focus on structural characterization and optical polarization efficiency of Ta/CoFeB/MgO spin injector grown on the top of an InGaAs-QW LED. We will show that for very thin layer of CoFeB it is possible to induce Perpendicular Magnetic Anisotropy leading to emission of polarized light at remanence (i.e. without external magnetic field). A natural extension of this magnetic bit conversion into circularly-polarized light via spin-polarized current is to extend the Spin-LED principle to Spin-LASER.

Based on our expertise on Spin-LEDs, we fabricated and characterized an optically pumped (100)-oriented InGaAs/GaAsP MQW Vertical External Cavity Surface Emitting Laser (VECSEL). Using an optical spin injection we were able to demonstrate a switching between two highly circular polarization states [4]. We will discuss the condition for the control of the electromagnetic field polarization.

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9167-4, Session 1b

Ultrafast adiabatic rapid passage in a single semiconductor quantum dot *(Invited Paper)*

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Adiabatic rapid passage (ARP) provides a robust optical control strategy for solid state qubit systems such as semiconductor quantum dots due to the insensitivity of this process to variations in optical parameters such as the transition energy and dipole moment. In this work, we present the demonstration of ARP on a single self-assembled InAs quantum dot. Through the use of broad bandwidth optical control pulses, our experiments explore a new regime of strong (and rapidly-varying) Rabi energies. We achieve ARP on a subpicosecond time scale, representing a 20 fold reduction in gate time relative to previous experimental demonstrations [1]. Our experiments also reveal a reduction in the efficiency of exciton inversion for negatively-chirped pulses in comparison to results for positive pulse chirp, confirming the dominance of resonant coupling to acoustic phonons in exciton dephasing during the control pulse. Calculations of the exciton dynamics using a density matrix treatment including coupling to LA phonons suggest the importance of multi-phonon emission processes and/or non Markovian effects. Together with the recent demonstration of parallel single qubit gates using optimal quantum control techniques [2], these results highlight the power and flexibility of optical pulse shaping for the control of solid state

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9167-5, Session 1b

Thermoelectric transport through nano-devices: interplay between resonance spin scattering and strong spin-orbit interaction *(Invited Paper)*

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We investigate the interplay between effects of Zeeman field and strong Spin-Orbit (SO) interaction in the single electron transistor (SET) built on a quantum dot strongly coupled to one of the leads by a single-mode quantum point contact (QPC). The quantum transport through such a device is described by Kondo physics. The role of the impurity spin in the ordinary Kondo problem is played by the orbital degrees of freedom: the left/right movers at QPC stand for the impurity spin-up/down projections in the conventional Kondo problem while two spin projections of an electron account for the scattering channels.

The impurity spin-flip process in the ordinary Kondo effect is represented in this model by the reflection in the QPC, with the Kondo coupling determined by the reflection coefficient.

The charging energy of a Coulomb blockaded quantum dot plays the role of a Kondo temperature.

On one hand, the external magnetic field applied to the SET in the strong-coupling regime is responsible for the Non-Fermi liquid -to-Fermi liquid crossover in the transport properties. A parallel magnetic field applied to SET results in the channel up/down asymmetry and thus changes the universality class from the two-channel Kondo to the single-channel Kondo regimes. On the other hand, if external magnetic field is smaller compared to effective field associated with the spin-orbit interaction, the thermoelectric coefficients depend on an angle between the Zeeman and SO fields allowing a fine-tuning a Fermi-liquid to Non-Fermi-liquid crossover by the in-plane magnetic field.

It is shown that the strong spin orbit interaction in QPC “protects” the Non-Fermi liquid regime associated with the two-channel Kondo effect and modifies the thermoelectric coefficients. We discuss how the effects of strong electron interaction and resonance scattering influence the thermoelectric transport through the nano-devices and present some suggestions for experimental verification of our theoretical predictions.

9167-6, Session 1b

Room-temperature initialization, dynamics, and measurement of coherent electron spins in strongly confined quantum dots *(Invited Paper)*

Jesse Berezovsky, Ahmad K. Fumani, Michael Wolf, Case Western Reserve Univ. (United States)

Semiconductor quantum dots provide a platform for studying and exploiting individual electron spins as they interact with a complex solid state environment. Colloidal nanocrystal quantum dots are of particular interest for potential applications, because they can achieve sufficient confinement to operate at room temperature with relatively robust electron spin coherence. The strong confinement in these nanostructures leads to significant effects caused by electron-hole exchange interactions, mixing of valence subbands, variation in particle size and shape, and surface defects. These effects all influence the processes of carrier spin initialization, dynamics, and detection. We have performed ensemble time-resolved Faraday rotation experiments as well as single-dot photoluminescence measurements to study how the strong quantum confinement affects the spin physics in these systems. We find that the mixing of valence subbands in the confined hole states largely determines the efficiency of optical spin pumping and Faraday-rotation-based spin detection. The intermittent charging of the quantum dots results in both photoluminescence blinking and changes to the coherent spin dynamics. Significant splitting of the exciton ground state due to the electron-hole exchange interaction and crystal fields leads to spin decoherence effects that depend sensitively on quantum dot size and shape. By studying these effects, we take a step towards controlling and exploiting spin coherence in this flexible room temperature platform.

9167-7, Session 1b

Epitaxial growth of CdMnTe quantum dots directly on Si(111) *(Invited Paper)*

Marielle H. Lage, Sukarno O. Ferreira, Univ. Federal de Viçosa (Brazil); Angelo S. Malachias, Univ. Federal de Minas Gerais (Brazil)

The presence of magnetic ions in a diluted magnetic semiconductor (DMS) leads to a variety of electronic, optical and magneto-optical properties. For instance, the exchange interaction between the magnetic ions spin and the spin of carriers leads to formation of bound magnetic polarons (BMPs). In a diluted magnetic quantum dot (DMQD), the possibility of tuning the three dimensional confinement originates new magnetic effects not present in bulk or quantum wells and makes MPs a very interesting system. Recently, formation of robust MPs has been observed in type-II DMQDs, due to the spatial separation of electrons and holes. In this work, we report the growth and structural characterization of CdMnTe/Si quantum dots. The samples were grown by molecular beam epitaxy directly on Si(111) substrates, in contrast with the previously studied systems, where the DMS islands were grown on II-VI buffers layers. The use of Silicon as substrates is advantageous for its compatibility with most processes of the microelectronic industry. We have used atomic force microscopy, high-resolution transmission electron microscopy and high-resolution x-ray diffraction to investigate the effect of growth time and temperature on the morphology and structural characteristics of the quantum dots. Our results show that this system follows the Volmer-Weber growth mode and almost perfect epitaxial islands can be grown despite a lattice mismatch around 19%. The introduction of a small concentration Mn ions reduces the lattice mismatch and improves the structural quality of the islands, as observed by reciprocal space maps around the (111) Bragg reflection.

9167-8, Session 2a

Optical spin orientation and depolarization in Ge: from near infrared to visible *(Invited Paper)*

Christian Rinaldi, Matteo Cantoni, Stefano Bertoli, Cristian Manzoni, Marco Marangoni, Giulio Cerullo, Massimiliano Bianchi, Roman Sordan, Riccardo Bertacco, Politecnico di Milano (Italy)

Ge-based spintronic devices have recently deserved great attention, thanks to the compatibility with Si-based electronics, the large carrier mobility, the opportunity of electrical spin manipulation and optical spin pumping.

In this work we employ fully epitaxial Fe/MgO/Ge heterostructures [1] to investigate the spectral dependence of the optical spin orientation in germanium at room temperature from near infrared (1550 nm) to visible (400 nm) [2].

We fabricated spin-photodiodes by optical lithography. Spin-polarized carriers are photo-excited in the semiconductor by monochromatic circularly polarized light. The spin-dependent tunneling at the Fe/MgO interface is employed to measure the degree of spin polarization (DSP) of both electrons and holes in Ge. Changing the photon energy and measuring the variation of the photocurrent upon reversal of light helicity, we were able to obtain the spectral dependence of DSP.

We found the expected maximum in the spin polarization of photocarriers [3] for excitation at the direct gap in Gamma (1550 nm) and a second sizable peak due to photo-generation in the L valleys (530 nm). Our data suggest distinct spin depolarization mechanisms for excitation at Gamma and L point of the Brillouin zone, with shorter spin relaxation times whether the X point is involved.

Ge-based spin-photodiodes pave the way to integrated detection of light helicity over a wide spectral range in novel spin-optoelectronics systems.

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9167-9, Session 2a

Optical orientation of electron spins in GaAs L-valleys *(Invited Paper)*

Andrea Balocchi, Phillipe Barate, Tiantian Zhang, Thierry Amand, Pierre Renucci, Hélène Carrère, Bernhard Urbaszek, Xavier Marie, Institut National des Sciences Appliquées de Toulouse (France)

Electron spin dynamics are more commonly performed with optical excitation energies close to the band gap yielding the photo-generation of spin-polarized electrons in the Γ valley. Information on the electron spin dynamics in the upper valleys could be of interest for devices based on electrical injection such as spin light-emitting diodes and spin lasers, where electrons populate not only the Γ valley but also the satellite L and X ones. Here we present an all-optical investigation of the electron spin dynamics of L-valleys in GaAs based on the optical orientation of L-valley electrons and a detection of the variation of the luminescence polarization at the fundamental gap transition. We demonstrate that a significant fraction of the electron spin memory can be conserved when the electron is scattered from the L to the Γ valley following an energy relaxation of several hundreds of meV. These measurements allow us to precisely quantify the energy-dependent optical orientation of L-electrons and the significant remaining polarization of electrons that relaxed to the bottom of the Γ valley. From both CW and time resolved measurements we deduce a typical L-valley electron spin relaxation time of 200 fs, in agreement with theoretical calculations.

9167-10, Session 2a

Demonstration of the spin solar cell effect *(Invited Paper)*

Dominique Bougeard, Bernhard Endres, Mariusz Ciorga, Maximilian Schmid, Martin Utz, Dieter Weiss, Günther Bayreuther, Christian H. Back, Univ. Regensburg (Germany)

Optical spin orientation is a well-known method to create spin accumulations in semiconductors. The mechanism is particularly efficient in direct bandgap semiconductors but requires the use of circularly polarized light and resonant excitation. Here, we present the demonstration of a spin-generating photovoltaic effect, which creates a spin accumulation in n-GaAs, using unpolarized and non-resonant illumination [1,2].

The device consists of a p-n junction built from n-doped GaAs and ferromagnetic (Ga,Mn)As as the p-side. The illumination of this junction creates a photo-voltage, causing electrons to tunnel across the junction. Due to the spin-dependent tunneling probability, a spin accumulation is then created in the n-GaAs. The spin solar cell effect is demonstrated both via complementary polar magneto-optic Kerr effect experiments and electrical non-local voltage detection. When applying a large negative bias the sign of the photo-induced spin polarization is reversed, as expected, due to the suppression of the tunneling current. This mode of operation corresponds to a spin photodiode. Both effects are expected to also be efficient at room temperature in indirect bandgap semiconductors, paving the way for efficient optical spin injection into silicon or germanium.

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9167-11, Session 2a

Spin-dependent transport as a consequence of Pauli blockade in a degenerate electron gas *(Invited Paper)*

Fabian Cadiz, Daniel Paget, Alistair Rowe, Ecole Polytechnique (France)

Degeneracy of a photoelectron gas strongly affects spin transport. The momentum relaxation time becomes spin dependent because of the Pauli Principle, resulting in a spin dependence of the mobility (μ) and the diffusion constant (D). In addition D is further modified because the usual Einstein relations are no longer valid. We report the observation of these phenomena in p+ GaAs as a function of photoelectron density and electronic temperature using a polarized microluminescence technique. In this method a highly spin-polarized photoelectron gas is locally created by a continuous, tightly-focused circularly-polarized laser and images of the resulting radial distribution of the spin polarization, P(r), are recorded. In non-degenerate conditions P decreases during transport (i.e. with increasing r) due to the usual spin relaxation processes. In contrast, at low temperatures and high excitation intensities the photoelectron gas becomes degenerate and the spin dependence of D and μ results in a spin filter effect in which P increases during transport. The results are interpreted, without any adjustable parameters, by solving the coupled spin and charge diffusion equations. Relative differences of 50 % and 30 % are found for the spin-dependent values of D and μ. The spin-dependence of the luminescence intensity profile is also explored, and the observation of a spin-dependent increase in the photoelectron volume confirms the central role played by the quantum degeneracy pressure.

9167-12, Session 2b

Spin-orbit interaction and spin coherence in narrow-gap semiconductor and semimetal wires *(Invited Paper)*

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The narrow-gap semiconductors InSb, InAs, and InGaAs, and the semimetal Bi have substantial spin-orbit interaction. We discuss spin-dependent quantum transport experiments on these materials, particularly in mesoscopic geometries on heterostructures and thin films, where spin-orbit interaction and quantum coherence determine the properties. The antilocalization signature in magnetoresistance results from spin-orbit interaction and is sensitive to spin- and quantum phase coherence lengths. Using antilocalization we determine the dependence of spin coherence lengths on the wire width in narrow nanolithographic ballistic InSb wires, InAs wires, and diffusive Bi wires. In all three different systems we find that the spin coherence lengths increase with decreasing wire widths if other parameters stay constant, an observation of technological importance for spin-based devices. A united understanding of the experiments can moreover be achieved via the duality between the Aharonov-Bohm and the Aharonov-Casher phases, the latter resulting from spin-orbit interaction. The experiments also indicate that Bi has surface states with strong Rashba-like spin-orbit interaction. In side-gated narrow channels of mesoscopic dimensions on InGaAs/InAlAs heterostructures, we study the tunable spin-orbit interaction induced by the electric field laterally confining electrons. The channel magnetoresistance due to antilocalization provides a measure of the confinement-induced spin-orbit interaction, if, as measurements

indicate, the variation in conducting width of the channel is also taken into account. This linear spin-orbit interaction, equivalent to an Aharonov-Casher vector potential, suggests the use of effective gauge fields to generate new quantum states of matter, with emphasis on edge states potentially robust against decoherence.

9167-13, Session 2b

Electron and hole spin transport in InSb nanowire quantum dots *(Invited Paper)*

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The spin-orbit interaction enables fast all-electrical control of individual spins in quantum dots. The presence of very large spin-orbit coupling thus makes InSb nanowires a highly promising platform for spin-based qubits. We rely on electric dipole spin resonance (EDSR) to demonstrate single electron spin rotations, measure the strength of the spin-orbit coupling and extract the anisotropic g-factor.

A promising approach to enhancing qubit coherence is to use hole spins as qubits instead of electron spins, since hole spins have weaker hyperfine coupling. Here we take advantage of the small bandgap of InSb to readily gate-tune our nanowire devices between few-electron and few-hole quantum dots. In the few-hole regime we demonstrate rotation of single hole spin states via EDSR and use this to extract the hole g-factors. Thanks to the high tunability of these devices we are able to compare important properties of electrons and holes, such as effective masses, g-factors and spin-blockade anisotropies. The ability to control and read out hole spin states paves the way for more coherent, all-electrical hole-spin qubits.

9167-14, Session 2b

High magnetic field spectroscopy of silicon donors for quantum information applications *(Invited Paper)*

Benedict Murdin, Ellis Bowyer, Univ. of Surrey (United Kingdom)

Shallow donor impurities in silicon, once frozen out at low temperature, share many properties in common with free hydrogen atoms [1]. They have long been the subject of spectroscopic investigation, but it is only very recently [2,3] that it has been possible to investigate the time-domain dynamics of orbital excitations such as the 1s to 2p, due to the difficulty of obtaining short, intense pulses in the relevant wavelength range. These new techniques make shallow donors, and also acceptors [4], attractive for studying atomic physics effects, and for applications in quantum information. We have measured the population dynamics [2] of electrons orbiting around phosphorus impurities in commercially-available silicon, and shown that the lattice relaxation lifetime is about 200ps, only 1 order of magnitude shorter than the radiative lifetime of free hydrogen. Recently we also showed that high magnetic fields can introduce enormous changes in the electron wavefunction [1], and that easily available fields could be used for spatial control of the Rydberg orbital, and hence the overlap with adjacent atoms.

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9167-15, Session 3a

Postselection-free entangled photons from highly symmetric quantum dots grown by droplet epitaxy *(Invited Paper)*

Takashi Kuroda, Takaaki Mano, Kazuaki Sakoda, National Institute for Materials Science (Japan); Bernhard Urbaszek, Institut National des Sciences Appliquées de Toulouse (France); Xavier Marie, Thierry Amand, Univ. de Toulouse (France); Hideaki Nakajima, Hidekazu Kumano, Ikuo Suemune, Hokkaido Univ. (Japan)

Entanglement is an essential resource for the implementation of quantum information processing. An efficient source of high-purity entangled photons is of particular importance since it would play a key role in realizing practical quantum key distributions. Semiconductor quantum dots have attracted much attention due to their appealing aspects such as the capability of on demand photon pair generations. Despite the concept being straightforward and analogous to that of an atomic cascade, experimental implementation has long been problematic due to inherent asymmetry in a common class of dots. The fine structure splitting of the intermediate exciton states makes radiative transition paths distinguishable, and thus strongly degrades or even dissolve quantum correlations in the emitted photons. Various attempts have been devoted to restoring the isotropic characteristics, but these methods would limit the potential scalability of dot-based photon sources. Here we report the generation of highly-entangled photons using a naturally symmetric quantum dot cascade. Our source consists of strain-free GaAs dots self-assembled on a triangular symmetric (111)A surface. The measured photons strongly violate Bell's inequality without postselection (S = 2.33 +- 0.06), which is an important step towards scalable quantum communication applications. The remaining decoherence channel of the photon source is ascribed to random nuclear spin fluctuations in and near the dot. Recent progress on the growth of telecommunication quantum dots on (111)A InP will be also reported.

9167-16, Session 3a

Spin-resolved study of direct band-gap recombination in bulk Ge *(Invited Paper)*

Fabio Pezzoli, Anna Giorgioni, Emanuele Grilli, Univ. degli Studi di Milano-Bicocca (Italy); Giovanni Isella, Politecnico di Milano (Italy); Mario Guzzi, Univ. degli Studi di Milano-Bicocca (Italy); Mario Guzzi, University of Milano-Bicocca (Italy)

Germanium and silicon-germanium alloys have found entry into Si technology thanks to their compatibility with Si processing and their ability to tailor electronic properties by strain and band-gap engineering. Noticeably, the quasi-direct band structure of Ge allows for optical spin orientation bridging the fields of spintronics and Si photonics where Ge is increasingly applied. Despite recent progress in the investigation of spin dynamics in Ge, very little is known about spin flip scattering by dopants and the role played by impurities in determining spin properties in different temperature regimes. Here we present a combined experimental and theoretical investigation of the spin and energy relaxation of electrons in Ge. By taking advantage of polarization-resolved photoluminescence measurements and Monte Carlo simulations of carrier dynamics we unveil a unique and very rich spin physics and highlight the importance of the multi-valley conduction band of this material. We demonstrate full control over the angular momentum of the direct gap emission with a complete reversal between right- and left-handed circular polarization. In the low temperature regime, the observed state of light polarization is ascribed to the so-far overlooked carrier cooling process that stems from the Coulomb scattering originated within the X-valleys. In the high temperature range, we disclose the role of backscattering from the L-valley in defining the depolarization of direct gap luminescence. This detailed investigation of spin properties of Ge is expected to open new opportunities connected to photonics and spintronics on a CMOS-compatible platform.

9167-17, Session 3a

Photonic spin Hall effect for precision metrology *(Invited Paper)*

Xinxing Zhou, Shizhen Chen, Yachao Liu, Hailu Luo, Shuangchun Wen, Hunan Univ. (China)

The photonic spin Hall effect (SHE) is generally believed to be a result of an effective spin-orbit interaction, which describes the mutual influence of the spin (polarization) and the trajectory of the light beam. For optical wavelengths, the photonic SHE is very weak and the corresponding spin-dependent splitting is restricted to a few tens of nanometers. However, using the quantum weak measurement, this tiny phenomenon can be detected with the desirable accuracy. The photonic SHE holds great potential for precision metrology owing to the fact that the spin-dependent splitting in photonic SHE are sensitive to the structural parameter variations of different physical systems. We should firstly establish the quantitative relationship between the spin-dependent shifts and the structural parameters. After detecting the spin-dependent displacements with weak measurement method, we can accurately determine these structural parameters. Here, we will present some of our works on using photonic SHE for precision metrology, such as determining the photon momentum in a transparent dielectric, measuring the thickness of nanometal film, identifying the graphene layers, and detecting the strength of axion coupling in topological insulators.

9167-18, Session 3a

On the charge-magnet paradoxes of classical electrodynamics *(Invited Paper)*

Masud Mansuripur, College of Optical Sciences, The Univ. of Arizona (United States)

A number of charge-magnet paradoxes have been discussed in the literature, beginning with W. Shockley's famous 1967 paper, where he introduced the notion of hidden momentum in electromagnetic systems. We discuss all these paradoxes in a single, general context, showing that the conservation laws of energy, momentum, and angular momentum can be satisfied “without” the need for hidden entities, provided that the Einstein-Laub law of force and torque is used in place of the standard Lorentz law. Einstein and Laub published their paper in 1908, but the simplicity of the conventional Lorentz law overshadowed the subtle features of the Einstein-Laub formulation which, at first sight, appears overly complicated. However, that slight complication turns out to lead to subsequent simplifications in light of the discovery of hidden momentum by Shockley in 1967, more than a decade after Einstein had passed away. In this presentation, we will show how the Einstein-Laub law solves the underlying problems associated with several paradoxes of classical electrodynamics -- without contradicting the existing body of knowledge that has been confirmed by 150 years of theoretical work and experimental observations in electrodynamics.

9167-19, Session 3b

Individual cobalt and manganese ions in semiconductor quantum dots and photonic structures *(Invited Paper)*

Wojciech Pacuski, Univ. of Warsaw (Poland)

This work presents fabrication and optical study of diluted magnetic semiconductors (DMS) and two kind of quantum dots (CdTe and CdSe) with individual ions of transition metals: cobalt and manganese [1,2]. The most surprising findings are related to exciton recombination channels. For DMS structures where exciton energy is larger than intraionic transition energy, we observe excitonic photoluminescence which is weak due to quenching by magnetic ions. However, for single magnetic ions in QDs, effect of quenching is negligible, as shown by exciton photoluminescence decay measurements [1].

QDs containing exactly one magnetic ion exhibit characteristic photoluminescence spectrum modified by s,p-d exchange interaction. Exciton line is split by 6 in case of single Mn2+ in CdSe QD [1] (due to 6 spin projection of Mn2+ [3]). In case of CdTe QD with individual Co2+, exciton line is split by 4 [1] (due to 4 spin projection of Co2+). Using on/off modulated non-resonant laser excitation we are determining spin relaxation of individual magnetic ions and we find the longest relaxation times for single Mn2+ in CdSe QDs [1].

Permanent marking of quantum dots position enable multiple studies on selected magnetic ion and fabrication of a micropillar cavity with a QD containing exactly one magnetic ion [2].

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9167-21, Session 3b

Conventional versus unconventional magnetic polarons: ZnMnTe/ZnSe and ZnTe/ZnMnSe quantum dots *(Invited Paper)*

Biplob Barman, Athos Petrou, Yutsung Tsai, Thomas A. Scrace, James M. Pientka, Joseph R. Murphy, Alexander N. Cartwright, Igor Zutic, Bruce D. McCombe, Univ. at Buffalo (United States); Rafal Oszwaldowski, Andre Petukhov, South Dakota School of Mines and Technology (United States); Ian R. Sellers, The Univ. of Oklahoma (United States); Wu-Ching Chou, W. C. Fan, National Chiao Tung Univ. (Taiwan); C. S. Yang, Tatung Univ. (Taiwan)

A magnetic polaron (MP) can be viewed as a cloud of localized magnetic ion spins, aligned through exchange interaction with the spin of a confined carrier. A conventional understanding suggests that the MP formation energy E(MP), measured from the red-shift of the band-edge photoluminescence (PL), decreases rapidly with an increase in temperature and applied magnetic field. Our time-resolved photoluminescence studies reveal differences in MP behavior in two related, spatially indirect, (II,Mn)VI, epitaxially grown quantum dot (QD) structures. In type-A ZnTe/(Zn,Mn)Se samples we observe E(MP) with a conventional temperature and magnetic field dependence. However, in type-B (Zn,Mn)Te/ZnSe samples there is only a weak dependence of E(MP) on temperature and magnetic field; E(MP) is also larger than that in type-A samples. We attribute these differences to the difference in the strength of the exchange interaction between the Mn and the hole spins, which are spatially separated in type-A, but in close proximity in type-B samples. Our theoretical analysis of the PL data in type-B samples suggest the presence of antiferromagnetic coupling of Mn spins which leads to an unusual form of magnetic ordering.

9167-22, Session 4a

Direct observation of non-thermal influence in the process of photo-induced ferromagnetic resonance in (Ga,Mn)As *(Invited Paper)*

Takashi Matsuda, Kazuhiro Nishibayashi, Hiro Munekata, Tokyo Institute of Technology (Japan)

Some works [1, 2] concerning the photo-induced ferromagnetic resonance (phi-FMR) in (Ga,Mn)As assumed that the resonance was triggered by the ultrafast spin heating (UFSH), despite of the fact that only a small fraction of photon energy could be released to spin and lattice sub-systems in ps time scale because of the presence of the

band gap. We report here that, through studying the initial stage of phi-FMR, magnetization precession is not accompanied by the UFSH but is triggered by the modulation of hole-mediated exchange interaction, in particular crystal magnetic anisotropy, through the repopulation of photo-excited holes. Our findings are based on time-resolved magneto-optical and reflectivity signals obtained from a Ga0.98Mn0.02As epilayer by pump-probe technique with fs-laser source in the regime of weak excitation (0.34 - 3.4 μJ/cm2 per pulse). One of the most remarkable results is a clear observation of the onset of the precession together with pump-probe autocorrelation signals in the sub-ps time scale with excitation wavelengths of $\lambda > 820$ nm. Analysis with the gyromagnetic model reveals a change in the direction of crystal anisotropy with duration of 10 – 20 ps. A characteristic exponential decay washes out the autocorrelation signals when excited with $\lambda > 820$ nm. Furthermore, duration of excited crystal anisotropy is extended up to 90 – 140 ps in this case. Since 820 nm corresponds to the photon energy equivalent to the band gap of a host GaAs, effects occurring with $\lambda \leq 820$ nm are attributed to the excitation of delocalized carrier system.

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9167-23, Session 4a

Modeling optically pumped NMR and spin polarization in GaAs/AlGaAs quantum wells *(Invited Paper)*

Christopher J. Stanton, Dipta Saha, Ryan Wood, Clifford R. Bowers, Univ. of Florida (United States); Erika L. Sesti, Sophia E. Hayes, Washington Univ. in St. Louis (United States)

Optically-pumped nuclear magnetic resonance (OPNMR) spectroscopy is an emerging technique to probe electronic and nuclear spin properties in bulk and quantum well semiconductors. In OPNMR, one uses optical pumping with circularly polarized light to create spin-polarized electrons in a semiconductor. The electron spin can be transferred to the nuclear spin bath through the Fermi contact hyperfine interaction which can then be detected by conventional NMR. The resulting NMR signal can be enhanced four to five orders of magnitude or more over the thermal equilibrium signal. In previous work, we studied OPNMR in bulk GaAs were we investigated the strength of the OPNMR signal as a function of the frequency of the pump laser. This allowed us to study the spin-split valence band. Here we report on OPNMR studies in AlGaAs/GaAs quantum wells. We will focus on the theoretical calculations for the average electron spin polarization at different photon energies for different values of external magnetic field in both unstrained and strained quantum wells. Our calculations allow us to identify the Landau level transitions which are responsible for the peaks in the OPNMR signal intensity. The calculations are based on the 8- band Pidgeon-Brown model generalized to include the effects of the quantum confinement potential as well as pseudomorphic strain at the interfaces. Optical properties are calculated within the golden rule approximation. Detailed comparison to experiment allows one to accurately determine valence band spin splitting in the quantum wells including the effects of strain.

9167-24, Session 4a

Experimental measurements of optically pumped NMR and spin polarization in bulk GaAs and AlGaAs/GaAs quantum wells *(Invited Paper)*

Sophia E. Hayes, Erika L. Sesti, Washington Univ. in St. Louis (United States); Dipta Saha, Ryan Wood, Clifford R. Bowers, Christopher J. Stanton, Univ. of Florida (United States)

Optically-pumped nuclear magnetic resonance (OPNMR) spectroscopy uses optical pumping of a direct-gap semiconductor (such as GaAs in bulk or quantum well form) to orient the electron spins. These electron spins couple to the surrounding nuclei through a Fermi-contact hyperfine interaction, thereby polarizing these as well. OPNMR uses the detection of 69Ga and 71Ga NMR resonances at low temperatures (4-10K) and at relatively low magnetic fields (3T – 7T). In previous work, we varied the photon energy used for optical pumping, as well as the polarization of the laser, to determine the behavior of the OPNMR resonances as a function of each of these parameters. These studies yielded information on the spin-split valence band. Here we report on OPNMR studies in AlGaAs/GaAs quantum wells. The talk will focus on new measurements of the quantum well and bulk signals at 3T and 4.7T, in particular as a function of laser intensity. In conjunction with theoretical calculations, Landau level transitions which are responsible for the peaks in the OPNMR signal intensity can be identified. The calculations, described in a separate paper from Stanton et al., are based on the 8- band Pidgeon-Brown model. Optical properties are calculated within the golden rule approximation. Detailed comparison to experiment allows one to accurately determine valence band spin splitting in the quantum wells, and a comparison to the behavior in bulk GaAs. This work was supported by the NSF through grants DMR-1206447, DMR-1105437, and the NHMFL In-House Science Program (DMR-1157490).

9167-25, Session 4a

Deviation from the Landau-Lifshitz-Gilbert equation in the inertial regime of the magnetization *(Invited Paper)*

Enrick Olive, Univ. de Tours (France)

The inertial dynamics of uniform magnetization is investigated in the framework of a generalized Landau-Lifshitz-Gilbert (LLG) equation wich introduces a characteristic time that accounts for fast degrees of freedom. Unlike the usual LLG equation where the dynamics is limited to the precession of the magnetization around a static field, a fast nutation dynamics coupled to the precession is evidenced in the generalized LLG equation. As a consequence, the resulting resonance curves in the frequency domain show two different peaks associated with both dynamics. Another consequence of the inertial model is the displacement of the ferromagnetic resonance (FMR) compared to the usual LLG equation. We present analytical and numerical simulation results on the expected resonance curves within the inertial model which is investigated while varying the fast characteristic time Ÿ, the damping and the static field.

9167-26, Session 4b

Domain walls in multiferroic oxides as nanoscale functional elements *(Invited Paper)*

Jan Seidel, The Univ. of New South Wales (Australia)

Interfaces and topological defects in complex oxide materials, such as domain walls, have recently received increasing attention due to the fact that their properties, which are linked to the inherent order parameters of the material, its structure and symmetry, can be completely different from that of the bulk material [1]. I will present an overview of recent results on electronic and optical properties of ferroelectric phase boundaries, domain walls, and topological defects in multiferroic BiFeO3 [2, 3]. The origin and nature of the observed confined nanoscale properties is probed using a combination of nanoscale transport measurements, high resolution transmission electron microscopy and first-principles density functional computations. I will also give an outlook on how these special properties can be found in other material systems and discuss possible future applications [4].

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9167-27, Session 4b

Resonant Raman scattering in $BiFeO_3$ *(Invited Paper)*

Mads Weber, Ctr. de Recherche Public - Gabriel Lippmann (Luxembourg) and Univ. du Luxembourg (Luxembourg); Mael Guennou, Ctr. de Recherche Public - Gabriel Lippmann (Luxembourg); Constance Toulouse, Maximilien Cazayous, Univ. Paris 7-Denis Diderot (France); Jens Kreisel, Ctr. de Recherche Public - Gabriel Lippmann (Luxembourg) and Univ. du Luxembourg (Luxembourg)

BiFeO3, being one of the very few materials having at ambient conditions both magnetic ordering and ferroelectricity, has been adopted as a model multifunctional material. Recent investigations have revealed notably its potential as a photoferroelectric, or the ubiquitous properties of its domain walls, thought of as basic functional elements in the currently emerging field of “domain-wall nanoelectronics”. Raman spectroscopy has been amply used in the past for characterization of BiFeO3 single crystals, ceramics and thin films. Its potential for characterization of domain-walls or nanostructures is unquestioned, but requires a thorough understanding of the Raman spectra of the bulk material and the many factors that influence it (excitation wavelength, skin layer, penetration depth etc.).

Here, we discuss the Raman spectrum of BiFeO3 with a focus on resonant Raman phenomena measured with a collection of exciting laser lines from 325 to 785 nm. Resonant Raman scattering occurs when the exciting laser light approaches an electronic excitation, and is usually of little significance in classical insulators with band gap lying well above the visible range. In BiFeO3 however, resonance phenomena are shown to be particularly pronounced with blue or green laser light and to affect both the first-order and the second-order phonon spectrum. The temperature dependence of these features enables us to link these observations to current understanding on the behaviour of the band gap and electronic phenomena in BiFeO3. We expect resonant Raman studies to be a very useful tool for investigations of interaction of light with BiFeO3.

9167-28, Session 4b

Low-dimensional antiferromagnetic transition metal oxides coupled to magnetic substrates *(Invited Paper)*

Alberto Brambilla, Andrea Picone, Michele Riva, Alberto Calloni, Giulia Berti, Gianlorenzo Bussetti, Marco Finazzi, Lamberto Duò, Franco Ciccacci, Politecnico di Milano (Italy)

Intriguing magnetic properties can be obtained in systems containing antiferromagnetic (AF) transition metal oxides both by low-dimensionality and by proximity to ferromagnetic (F) layers, giving rise to well-known exchange coupling phenomena. The tailoring of such properties towards spintronics applications must pass through a sound understanding of the correlations between their magnetic, chemical, structural and morphologic features.

So far, we have collected a rich record of investigations on AF/Fe layered structures [1]. Several issues, such as chemical interactions at the interfaces, magnetic couplings in AF/Fe and Fe/AF/Fe systems, spin reorientation transitions, development of nanometer sized domains and very sharp domain walls, have been investigated.

We are currently pursuing new efforts towards the nanoscale understanding of AF/F structures by studying the early stages of formation of oxide nanostructures coupled to Fe substrates. Such systems contain appealing ingredients, such as high chemical reactivity, stabilization of unusual stiochiometries, presence of metastable phases. Our presentation will focus on Scanning Tunneling Microscopy/Spectroscopy investigations of transition metal oxides nanostructures based on Co, Ni and Cr [2,3]. Such investigations are supported by electron spectroscopies – also with spin resolution –by x-ray magnetic dichroism and magneto-optical Kerr effect measurements. The results will be discussed in the perspective of a comparative study aimed to identify the key features to develop new nanostructured magnetic structures with a bottom-up approach.

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9167-29, Session 4b

Magnetization dynamics and Gilbert damping properties of Co_2FeAl film grown by molecular beam epitaxy *(Invited Paper)*

Shuag Qiao, Shuaihua Nie, Institute of Semiconductors (China); Yan Huo, Yizheng Wu, Fudan Univ. (China); Jianhua Zhao, Xinhui Zhang, Institute of Semiconductors (China)

Co-based full-Heusler alloys have been revealed to behave like half-metals even at room temperature. The highly ordered Co2FeAl with an ideal L21 structure has been predicted to be half-metal, with a well-defined band gap in the minority spin channel. However, its magnetic and damping properties, which are fundamental for spintronics application, have not been investigated in detail before. In this work, the thickness and growth temperature dependent magnetocrystalline anisotropy of MBE-grown Co2FeAl films were first investigated by employing the rotating magneto-optical Kerr effect (ROTMOKE). Then the magnetization dynamics and Gilbert damping property for high quality Co2FeAl films were investigated in detail by combining both the ferromagnetic resonance (FMR) and time-resolved magneto-optical Kerr effect (TR-MOKE) techniques. The apparent damping parameter was found to show strong dependence on both the strength and directions of the applied magnetic field at low field regime, but decrease drastically with increasing magnetic field for all studied films with different thickness and eventually become a constant value of 0.004 at high field regime. The inhomogeneity of effective magnetocrystalline anisotropy and two-magnon scatterings are suggested to be responsible for the observed abnormal damping properties observed especially at low field regime. The intrinsic damping parameter of 0.004 is deduced for our highly ordered Co2FeAl film. Our results provide essential information for highly ordered MBE-grown Co2FeAl film and its possible application in spintronic devices.

9167-30, Session 4b

Ultra-low-energy straintronics using multiferroic composites *(Invited Paper)*

Kuntal Roy, Purdue Univ. (United States)

The primary impediment to continued improvement of traditional charge-based electronic devices in accordance with Moore's law is the excessive energy dissipation that takes place in the device during switching of bits. One very promising solution is to utilize multiferroic composites, i.e., ferroelectric-ferromagnet heterostructures, where the magnetoelectric effect arises from the strain-mediated interaction between the ferroelectric and ferromagnetic constituents. The voltage applied across the heterostructure generates a strain in the magnetostrictive ferromagnet and thereby the induced magnetic anisotropy can rotate its magnetization. With suitable choice of materials, the required voltage for magnetization switching can be a few millivolts, that incurs a miniscule amount of energy dissipation of ~1 attojoule [1-4]. Such devices have been proposed not only for memory bits, but also for building logic [5,6] leading to a new field named straintronics [7]. Apart from digital computing, it is shown that the multiferroic devices can be also utilized for analog signal processing, e.g., voltage amplification with a gain and input-output isolation, filter, rectifier. It is also shown that in a magnetostrictive nanomagnet, it is possible to achieve the so-called Landauer limit (or the ultimate limit) of energy dissipation. According to

Landauer's principle, postulated by the famous scientist R. Landauer back in 1961, it necessarily dissipates an energy of amount kT ln(2) compensating the entropy loss while erasing a bit of information, thereby linking information and thermodynamics. The simulation results are based on the study of magnetization dynamics using the stochastic Landau-Lifshitz-Gilbert (LLG) equation in the presence of room-temperature thermal fluctuations.

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9167-31, Session 4b

Persistent optically induced magnetism in oxygen-deficient strontium titanate *(Invited Paper)*

William D. Rice, Los Alamos National Lab. (United States); Palak Ambwani, Univ. of Minnesota (United States); M. Bombeck, Technische Univ. Dortmund (Germany); Joe D. Thompson, Los Alamos National Lab. (United States); Greg Haugstad, Univ. of Minnesota, Twin Cities (United States); Chris Leighton, Univ. of Minnesota (United States); Scott A. Crooker, Los Alamos National Lab. (United States)

Strontium titanate ($SrTiO_3$) is a foundational material in the emerging field of complex oxide electronics. $SrTiO_3$ has recently become a renewed materials research focus due to observations of extremely high interfacial charge densities that form between $SrTiO_3$ and other wide bandgap semiconducting oxides. Investigations of $SrTiO_3$ heterostructure interfaces were further catalyzed in part by the unexpected discovery of the coexistence of magnetism and superconductivity. The formation and distribution of oxygen vacancies, especially in $SrTiO_3$, is thought to play an essential but as-yet-incompletely understood role in these effects.

Using magnetic circular dichroism spectroscopy and SQUID magnetometry, we find that oxygen-deficient $SrTiO_{3-\sigma}$ exhibits persistent, optically induced magnetization [1]. We find that when oxygen vacancies are introduced via thermal annealing in UHV, we are able to optically induce magnetization at zero magnetic field with sub-bandgap (400-500 nm) circularly polarized light; this magnetization inverts when the circular polarization is reversed. Interestingly, we observe that the relaxation dynamics strongly depend on temperature: the induced magnetization exhibits hours-long decay times when the temperature is below 10 K, but only persists for seconds near 18 K, the temperature where the magneto-optical effects first appear. Utilizing the remarkably long relaxation times and all-optical magnetization control, we demonstrate that $SrTiO_{3-\sigma}$ can be used as optical magnetic memory. The magneto-optical phenomena described here, which only occur in oxygen-deficient samples, reveal the detailed interplay between magnetism, lattice defects, and light in an archetypal oxide material and may yield new insights into the physics of oxide interfaces.

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9167-32, Session 5

Dynamics and topological mass of skyrmionic spin structures *(Invited Paper)*

Christoforos Moutafis, Paul Scherrer Institut (Switzerland); Felix Büttner, Johannes Gutenberg Univ. Mainz (Germany) and Technische Univ. Berlin (Germany); Andre Bisig, Johannes Gutenberg Univ. Mainz (Switzerland); Benjamin Krüger, Johannes Gutenberg Univ. Mainz (Germany); C. A. F. Vaz, Paul Scherrer Institut (Switzerland) and Johannes Gutenberg Univ. Mainz (Germany); Michael Foerster, Mohamad-Assaad Mawass, Johannes Gutenberg Univ. Mainz (Germany); Michael Schneider, Christian Gunther, Technische Univ. Berlin (Germany); Jan Geilhufe, Technische Univ. Eindhoven (Germany); C. von Korff Schmising, J. Mohanty, B. Pfau, Stefan Schaffert, Technische Univ. Berlin (Germany); Tomek Schulz, Johannes Gutenberg Univ. Mainz (Germany); Markus Weigand, Max-Planck Institut für Intelligente Systeme (Germany); Henk J. M. Swagten, Technische Univ. Eindhoven (Netherlands); Jörg Raabe, Paul Scherrer Institut (Switzerland); Mathias Kläui, Johannes Gutenberg Univ. Mainz (Germany); Stefan Eisebitt, Technische Univ. Berlin (Germany) and Helmholtz-Zentrum Berlin fur Materialien und Energie GmbH (Germany)

Skyrmions are topologically protected particle-like configurations, with a topological complexity described by their Skyrmion number. In magnetic systems, they have been numerically predicted to exhibit rich dynamics, such as the gyrotropic and breathing modes, dominated by their topology. Recent experimental advances brought their static manipulation well under control. However, their dynamical behaviour is largely unexplored experimentally. In this work, we provide with the first direct observation of eigenmode skyrmion dynamics. In particular, we present dynamical imaging data with high temporal and spatial resolution to demonstrate the GHz gyrotropic mode of a single skyrmion bubble, as well as the breathing-like behaviour of a pair of skyrmionic configurations. We use the observed dynamical behaviour to confirm the skyrmion topology and show the existence of an unexpectedly large inertia that is key for accurately describing skyrmion dynamics. Our results demonstrate new ways for experimentally observing skyrmion dynamics and provide a framework for describing their behaviour. Furthermore, the results outline a link between the dynamical behaviour of skyrmions and their distinct topological properties, with possible ramifications for skyrmionic spin structures research including technological applications.

9167-33, Session 5

Micromagnetics with Dzyaloshinskii-Moriya interaction: from domain walls to skyrmions *(Invited Paper)*

Stanislas Rohart, Univ. Paris-Sud 11 (France)

Recent observation using have shown that in ultrathin films in asymmetric multilayer stacks, chiral magnetic textures may appear, due to the Dzyaloshinskii-Moriya interaction (DMI) [1,2]. This opens the way to high efficiency current induced domain wall motion [2,3] or new type of memories based on skyrmions [4].

In this talk, we review different manifestations of DMI on these films. We first consider moderate DMI which doesn't destabilize the ferromagnetic ground state. The symmetry of DMI imposes a Néel structure with a unique chirality. These walls have unique properties such as increases Walker velocity and high sensitivity to the spin Hall effect spin-transfer torque [3]. Another manifestation occurs at the nanostructure edges where a chiral magnetization tilt develops [6], which has practical consequences on edge domain wall nucleation [7].

In a second part we consider skyrmions which may appear for stronger DMI, and describe the conditions to obtain them as soliton states, in the perspectives of race-track memory type applications. We also show that the DMI induced edge micromagnetic state creates a confining potential for skyrmions which are then stable in nanostructures [6].

We acknowledge funding from ANR (ESPERADO Project).

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[5] O. Boulle et al. Phys. Rev. Lett. 111, 217203 (2013)

[6] S. Rohart and A. Thiaville Phys. Rev. B 88, 184422 (2013)

[7] S. Pizzini et al. submitted

9167-34, Session 5

Writing and deleting single magnetic skyrmions *(Invited Paper)*

Niklas Romming, Christian Hanneken, Matthias Menzel, Jessica E. Bickel, Boris Wolter, Kirsten von Bergmann, André Kubetzka, Roland Wiesendanger, Univ. Hamburg (Germany)

Magnetism in thin films can significantly deviate from commonly known magnetic configurations in bulk systems due to low dimensionality, hybridization effects, a change of the lattice constant, stacking and broken inversion symmetry at interfaces. This can lead to non-collinear spin states such as spin spirals or skyrmions. Especially magnetic skyrmions with their nontrivial topology are interesting objects for both fundamental as well as application-related research due to their possible utilization in data storage concepts.

Here, we report on an ultrathin magnetic film in which individual skyrmions can be written and deleted in a controlled fashion with locally injected spin-polarized currents from a scanning tunneling microscope [1]. An external magnetic field is used to tune the energy landscape, and the temperature is adjusted to prevent thermally activated switching between topologically distinct states. Switching rate and direction can then be controlled by the parameters used for current injection. The creation and annihilation of individual magnetic skyrmions demonstrates the potential for topological charge in future information-storage concepts.

[1] N. Romming et al.: Science 341, 636 (2013)

9167-35, Session 5

Skyrmions and helicoids in epitaxial thin film helical magnets *(Invited Paper)*

Theodore L. Monchesky, Murray N. Wilson, Dalhousie Univ. (Canada); Filipp N. Rybabov, Institute of Metal Physics (Russian Federation); Anna B. Butenko, Alexei B. Bogdanov, Ulrich K. Rossler, Leibniz-Institut für Festkörper- und Werkstoffforschung Dresden (Germany); Helmut Fritzsche, Canadian Neutron Beam Centre (Canada); Kathryn Krycka, Brian J. Kirby, National Institute of Standards and Technology (United States); James C. Loudon, Univ. of Cambridge (United Kingdom); Michael D. Roberston, Acadia Univ. (Canada); Simon Meynell, Eric A. Karhu, David Lake, Andrew S. Quigley, Dalhousie Univ. (Canada); Charles F. Majkrzak, National Institute of Standards and Technology (United States)

Currently, nanolayers of cubic chiral magnets are the only material system where magnetic skyrmions and helicoids are observed over a broad range of thermodynamic parameters. These magnetic states are promising candidates for novel spintronic applications. I will present an overview of the structure and magnetic properties of chiral magnet epilayers grown on Si(111), including MnSi, FeGe and (Fe,Co)Si, which opens the study of skyrmions to a broad range of characterization tools [1,2] that enables the resolution of a controversy in the literature about these nanolayers.

The presence of surfaces produce novel discrete helicoidal states in the epilayers that can be read by electrical means, which shows that in principle they could be used for information storage. The epitaxy induced out-of-plane uniaxial anisotropy is another key component that influences the magnetic texture. The sign of the anisotropy dictates how the skyrmions are stabilized. In contrast to films with an easy-axis, the hard-axis anisotropy entirely suppresses skyrmions in out-of-plane magnetic fields, as predicted by theoretical calculations.[2] An easy-plane anisotropy, however, stabilizes a novel skyrmion state consisting of elliptically distorted skyrmion gratings with their core magnetizations pointing in the plane of the film. Collectively, these results help to understand the general problem of skyrmion formation in chiral magnets. In this talk I will overview neutron scattering, magnetometry, and Lorentz microscopy measurements to provide a comprehensive view of skyrmions in chiral magnet epilayers.

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[2] Wilson et al., arXiv:1311.1191

9167-36, Session 5

Interaction between vortex walls and asymmetric notches in Permalloy nanowires *(Invited Paper)*

Luiz Sampaio Lima, Centro Brasileiro de Pesquisas Físicas (Brazil)

We have investigated the injection and transmission of vortex domain walls in Permalloy (Py) nanowires through triangular notches. We have used magneto-optical Kerr microscopy and micromagnetic simulations. The nanowires have the width varying from 300 to 800nm and were grown by e-beam lithography. The triangular notches are asymmetric and have in both sides the slope phi varying from 15 to 45 degrees, so two sets of samples were used: 45-phi and phi-45. The Kerr system is able to measure a single nanowire.

Measuring the hysteresis after the notch we observed that the domain wall pinning by the notch depends upon the vortex chirality, independent of the size and the symmetry of the notch. Counterclockwise (CCW) chirality always exhibit larger coercivity than clockwise (CW) one, and this effect was found more pronounced to the phi-45 set. It was also noticed different probabilities for the CCW and CW chiralities to be observed after the notch although both are produced with the same probability. For example, measured histograms of the CCW and CW coercivities show that CW has 9 times more probability than the CCW to be observed after the notch. It was measured for the 15-45 notch in head-to-head walls. It means that the interaction between the vortex wall and the notch is able to change the vortex chirality. Using the experimental results and micromagnetic simulations we were able to obtain the potential produced by the notch on the vortex wall.

9167-37, Session 6

Current-driven dynamics of chiral domain walls *(Invited Paper)*

Geoffrey S. Beach, Massachusetts Institute of Technology (United States)

In most ferromagnets the magnetization rotates from one domain to the next with no preferred handedness. However, broken inversion symmetry can lift the chiral degeneracy, leading to topologically rich spin textures such as spin-spirals and skyrmions via the Dzyaloshinskii-Moriya interaction (DMI) [1,2]. Here we show that in ultrathin metallic ferromagnets sandwiched between a heavy metal and an oxide, the DMI stabilizes chiral domain walls (DWs) whose spin texture enables extremely efficient current-driven motion [3]. We show that spin torque from the spin Hall effect drives DWs in opposite directions in Pt/CoFe/MgO and Ta/CoFe/MgO, which can be explained only if the DWs assume a Néel configuration with left-handed chirality. We directly confirm the DW chirality and rigidity by examining current-driven DW dynamics with magnetic fields applied perpendicular and parallel to the spin spiral [3,4]. This work identifies the origin of efficient current-driven domain wall motion in heavy metal/ferromagnet bilayers, and highlights a new path towards interfacial design of spintronic devices. In collaboration with S. Emori, U. Bauer, S.-M. Ahn, and E. Martinez.

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[4] S. Emori, et al., arXiv:1308.1432 (2013).

9167-38, Session 6

Helical order in one dimensional semiconductors *(Invited Paper)*

Peter Stano, RIKEN (Japan)

I will talk about the helical spin order which arises in the thermodynamical equilibrium in a one-dimensional (semi)conductor with spin impurities (e.g., nuclear spins, or spins of localized magnetic impurities). The helical order in localized spins is a consequence of the dimensionality, and thus very general, arising in metals, semiconductors, and even gapped phases, like superconductors.

I will show that the order follows from the resonant peak of the response (spin susceptibility) of a one-dimensional system. I will discuss recent low temperature transport experiments with semiconducting wires which suggest that such helical order was established in nuclear spins of atoms of the wire.

I will explain how such a helical order can be useful in the semi-super hybrid platform to stabilize Majorana fermions and to produce even more exotic many body excitations like fractionally charged fermions and parafermions.

9167-39, Session 6

Direct observation of a highly spin-polarized organic spinterface at room temperature *(Invited Paper)*

Wolfgang Weber, Fatima Djeghloul, Fatima Ibrahim, Institut de Physique et Chimie des Matériaux de Strasbourg (France); Matteo Cantoni, Politecnico di Milano (Italy); Martin Bowen, Loic Joly, Samy Boukari, Institut de Physique et Chimie des Matériaux de Strasbourg (France); Philippe Ohresser, Francois Bertran, Patrick Lefevre, Synchrotron SOLEIL (France); Pardeep Thakur, ESRF - The European Synchrotron (France); Fabrice Scheurer, Institut de Physique et Chimie des Matériaux de Strasbourg (France); Toshio Miyamachi, Karlsruher Institut für Technologie (Germany); Richard Mattana, Pierre Seneor, Unité Mixte de Physique CNRS/Thales (France); Ali Jaafar, Institut de Physique et Chimie des Matériaux de Strasbourg (France); Christian Rinaldi, Politecnico di Milano (Italy); Saquib Javaid, Jacek Arabski, Jean-Paul Kappler, Institut de Physique et Chimie des Matériaux de Strasbourg (France); Wulf Wulfhekel, Karlsruher Institut für Technologie (Germany); Nicholas B. Brookes, ESRF - The European Synchrotron (France); Riccardo Bertacco, Politecnico di Milano (Italy); Amina Taleb, Synchrotron SOLEIL (France); Mebarek Alouani, Eric Beaurepaire, Institut de Physique et Chimie des Matériaux de Strasbourg (France)

Toward the design of large-scale electronic circuits that are entirely spintronics-driven, organic semiconductors have been identified as a promising medium to transport information using the electron spin. This requires an organic current source that is highly spin-polarised at and beyond room temperature, but this key building block is still lacking. We experimentally and theoretically show how the interface between Co and phthalocyanine molecules constitutes a promising candidate. Spin-polarised direct and inverse photoemission experiments reveal a high degree of spin polarisation at room temperature at this interface. We measured a magnetic moment on the molecule's nitrogen ? orbitals, which substantiates an ab-initio theoretical description of highly spin-polarised charge conduction across the interface due to differing spinterface formation mechanisms in each spin channel. We propose, through this example, a recipe to engineer simple organic-inorganic interfaces with remarkable spintronic properties that can endure well above room temperature.

9167-40, Session 6

Molecular nanomagnetics for spintronic devices *(Invited Paper)*

Marco Affronte, Univ. degli Studi di Modena e Reggio Emilia (Italy)

The possibility of tailoring their functionalities at the molecular scale makes molecular nanomagnets interesting for applications in information technologies where the race for extreme miniaturization will soon lead at requiring components of few nanometers in size. Properties like the magnetic bistability or the switchability by external stimuli actually allow to mimic, at the molecular scale, basic operations commonly used in computers while embedding magnetic molecules in suitable electronic circuits allows the fabrication of novel spintronic devices. Even more challenging is the control and the exploitation of quantum properties in molecular spin clusters that may allow the encoding of quantum information with molecules. These concepts are substantiated by many achievements obtained in the recent years and they will be briefly reviewed in the first part of my talk [1]. Then, I shall focus on some viable molecular paths to fabricate novel spintronic devices made of carbon allotropes and molecular nanomagnets. As a first step, we have explored different strategies to efficiently graft molecular nanomagnets on carbon surfaces [2, 3]. Secondly, I shall present the design and the realization of hybrid devices made by graphene nano-constrictions with sizes down to 10nm decorated with TbPc2 magnetic molecules. The magnetization reversal of the molecules in proximity with graphene is detected by the magnetoconductivity of these hybrid devices, which shows the uniaxial magnetic anisotropy typical of the TbPc2 SMMs. These results depict the behavior of multiple-field-effect nano-transistors with sensitivity at the single-molecule level [5].

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9167-41, Session 7

Cyclotron resonance in ferromagnetic semiconductors at ultrahigh magnetic fields *(Invited Paper)*

Yasuhiro H. Matsuda, The Univ. of Tokyo (Japan)

Electronic states of ferromagnetic InMnAs and InMnSb films have been studied by the cyclotron resonance (CR) in ultrahigh magnetic fields of up to 140 T. [1] We used four MOVPE-grown InMnAs and InMnSb films and two MBE-grown InMnSb films. The three MOVPE-grown InMnAs films have the Mn contents x =1, 2, 4%, respectively, and the Currie temperatures (TC) are all 330 K, and the MOVPE-grown InMnSb film with x =5.6% has the Tc=590 K. The MBE grown InMnSb films with x=2% have the TC=10 K. The hole densities are around 10^18 cm-3 and 10^20 cm-3 for MOVPE films and MBE films, respectively.

CR is a powerful tool to investigate the electronic state of semiconductors. Since the mobility of the ferromagnetic semiconductors is typically as low as μ=100 cm2/(Vs), the CR experiment requires an ultrahigh magnetic field as high as B=100 T to satisfy the condition μB > 1. In the present study, we utilize the single-turn coil technique [2] that generates pulsed fields over 100 T with the coil destruction.

By analyzing the CR spectra using a model based on the 8-band k•p Pidgeon-Brown model, it is found that the CR features are well explained by the transitions in the valence band. [1] Our findings indicate that the impurity band is absent in the midgap and that the difference of the TC between the MOVPE-grown and MBE-grown films can be due to the difference of the hole densities.

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9167-42, Session 7

Magneto-optical spectroscopy of narrow gap ferromagnetic semiconductors *(Invited Paper)*

Giti A. Khodaparast, Virginia Polytechnic Institute and State Univ. (United States); Yasuhiro H. Matsuda, The Univ. of Tokyo (Japan); Dipta Saha, Gary D. Sanders, Christopher J. Stanton, Univ. of Florida (United States); Bruce W. Wessels, Northwestern Univ. (United States)

We present experimental and theoretical studies of the magneto-optical properties of p-type

narrow gap ferromagnetic semiconductors in ultrahigh magnetic fields. Samples were fabricated by Metal-Organic Vapor Phase Epitaxy (MOVPE) and demonstrate Curie temperatures above the room temperature. We compared Landau level and band structure calculations with observed Cyclotron Resonance measurements. To model the results, we used an 8-band Pidgeon-Brown model generalized to include the wave vector dependence of the electronic states along kz as well as the s-d and p-d exchange interactions with the localized Mn d-electrons. The Curie temperature is taken as an input parameter and the average Mn spin is treated in mean field theory. Our calculations indicate that the lower carrier densities in this material system can result in a much larger average spin compared to the MBE grown structures. This fact could be responsible for higher Curie temperatures in the MOVPE grown narrow gap ferromagnetic semiconductors.

The work was supported by the NSF through awards DMR-0846834 (Career), DMR-0804479, DMR-1305666, DMR-1157490 (GDS,CJS) and by the National High Magnetic Field Laboratory(DS), which is supported by National Science Foundation Cooperative Agreement No. DMR-0654118, the State of Florida, and the US Department of Energy.

9167-43, Session 7

g-factor anisotropy driven spin relaxation in germanium *(Invited Paper)*

Pengke Li, Jing Li, Univ. of Maryland (United States); Song Yang, Lan Qing, Hanan Dery, University of Rochester (United States); Ian Appelbaum, Univ. of Maryland (United States)

In semiconductors possessing more than a single conduction band valley, g-factor anisotropy opens a new channel of electron spin relaxation. This unusual mechanism arises in a magnetic field because the effective Zeeman field is tilted along the valley axis, and is randomized when electrons undergo intervalley scattering. This fluctuation depolarizes electron spins, similar to the Dyakonov-Perel mechanism in noncentrosymmetric semiconductors where spin relaxation is driven by a wavevector dependent magnetic field. We study the unique nature of g-factor anisotropy spin relaxation by spin transport measurements from long-distance germanium devices in a magnetic field aligned to the initial spin orientation. The confluence of electron-phonon scattering (leading to Elliott-Yafet spin relaxation) and this previously unobserved physics enables the extraction of spin lifetime solely from spin-valve measurements. We find spin lifetimes in Ge up to several hundreds of ns at low temperature, far beyond any other available experimental results. such long spin lifetime in Ge is governed by the space inversion symmetry and time reversal symmetry of electrons near the Brillouin zone L-point. Electric field and magnetic field are used to manipulate the spin signal by accelerating the spin polarized electrons and generating carrier heating, or by inducing Hanle spin precession.

9167-44, Session 7

Time resolved magneto-optical studies of InAsP ternary alloys *(Invited Paper)*

Brenden A. Magill, Michael A. Meeker, Travis R. Merrit, Giti A. Khodaparast, Virginia Polytechnic Institute and State Univ. (United States); Stephen A. McGill, National High Magnetic Field Lab. (United States); Chris J. Palmstrom, Univ. of California, Santa Barbara (United States)

Recently, g-factor engineering [1] has attracted much attention for potential applications in in the area of spintronics. InAsP ternary alloys can offer a unique feature, where a wide range of g- factors, including g=0 can be achieved. In this work, we employ magneto-PL, time-resolved magneto-PL, in addition to the time and polarization-resolved differential transmission measurements, to probe the band structure as well the carrier and spin relaxation dynamics in several InAsxP1-x alloys with compositions ranging from x=0.4 to 0.75. The samples were grown on Fe-doped semi-insulating InP(001) by chemical beam epitaxy.

To probe the band structure of these materials, we measured their photoluminescence (PL) in the near-infrared range at 4K and 300K and performed magneto-PL measurements from 0-25T between 4-90K. We observed two peaks in the PL which we attribute to free and bound excitons in the material. The wavelength of these peaks is blue shifted with increasing field as we would expect from theory.

We also report on time resolved differential transmission measurements using an ultra-fast laser with the pump and probe pulses tuned to range of wavelengths between 1280nm and 1350nm at 77 and 300K. To probe the spin relaxation as well as the carrier relaxation we can take advantage of interband selection rules to create spin polarized charge carriers with circularly polarized light. The polarization (P) is then given by P=(SCP-OCP)/(SCP+OCP) and we can use the decay of the polarized transmission to find the spin relaxation time.

Our results presented here demonstrate the tunability of the spin and carrier lifetimes in InAsP alloys as a function of alloy concentration, temperature, and external magnetic field.

ACKNOWLEDGMENT

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9167-45, Session 8

Properties of CoFeB-MgO magnetic tunnel junctions down to 11 nm *(Keynote Presentation)*

Hideo Ohno, Tohoku Univ. (Japan)

Properties of perpendicular CoFeB-MgO magnetic tunnel junction down to 11 nm in diameter are presented and discussed. The recording layer employed here consists of two CoFeB layers separated by a thin (0.4 nm) Ta layer. Tunnel magnetoresistance does not depend on the junction size while the thermal stability start to decrease at 30 nm. Scaling properties will be discussed.

9167-46, Session 8

Characterization of retention times and critical currents of STT-MRAM cells *(Invited Paper)*

Alexey Khvalkovskiy, Volodymyr Voznyuk, Sebastian Schafer, Dmytro Apalkov, Robert Beach, Vladimir Nikitin, SAMSUNG Electronics Co., Ltd. (United States)

The retention times t_ret and the critical switching current I_c0 of a STT-MRAM cell may be characterized by measuring the switching current I_c as a function of the switching pulse duration tsw for relatively long pulses (microseconds to seconds) and then extrapolating it to short pulses (tens of ns) to get I_c0 and to zero current to get the retention times. For the in-plane MTJs it has been well established, both theoretically and experimentally, that log(t_sw) is a linear function of I_c, which is successfully used to extract t_ret and I_c0 from the switching data for long pulses. For the perpendicular cells, it is also often assumed that this linear relationship is valid ([1] and references therein). However, it was shown recently that solution of the Fokker-Planck equation [2] and numerical simulations [3] predict quadratic relationship between log(t_sw) and I_c for the perpendicular cells. Indeed, we find experimentally, that the relationship between log(t_sw) and I_c is strongly non-linear, yet is not exactly quadratic. We will discuss the impact which the Joule heating and other artifacts have on determination of t_ret and I_c0 from the switching data.

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9167-47, Session 8

Status and outlook of STT-MRAM development *(Invited Paper)*

Tai Min, IMEC (Belgium)

Spin torque transfer (STT) MRAM has emerged as the most promising candidate for future L2/L3 cache and DRAM replacement due to its non-volatility, fast read and write time, small size, infinite endurance and compatibility with CMOS technology. There still many remaining challenges to be overcome for STT-MRAM to be commercialized as disruptive memory technology, especially at sub-20nm dimension and dense array: lowering the critical switching current while maintaining adequate thermal energy barrier, increasing tunneling magneto-resistance(TMR) and controlling the resistance distribution, developing re-disposition-free and edge-damage-free patterning process and robust MgO barrier for enough separation between switching and the breakdown voltage. In this talk, we will review the recent progress and future outlook of IMEC's STT-MRAM program. We have developed super smooth bottom electrode process: 0.5A roughness via optimization of CMP process and selection of electrode material. Positive effects on MTJ's PMA, TMR and 400oC post annealing stability observed. Reactive-Ion-Etching process with dynamic in-situ encapsulation for 100nm pitch dense array was developed with demonstration of reliable stop-on-MgO capability. MgO and CoFeB edge damage and its detrimental effect on device properties was observed and improved via process optimization. Effect of lithography technologies like 193i versus EUV on MTJ cell area hence resistance variation were investigated: substantial improvement can be achieved if EUV Self-Aligned Double Patterning process is utilized. Test chip with 1.6 Giga-bit 25nm MTJ at 100nm pitch array to investigate the tail bit behavior and etching process robustness at small-size-dense-array was developed and results will be discussed at the conference.

9167-48, Session 9

Progresses on STT-MRAM technology and normally-off system *(Invited Paper)*

Hiroaki Yoda, Toshiba Corp. (Japan)

Progress on STT- MRAM

Field writing MRAMs were developed. But the density has been limited to be below 64 Mbits which was far smaller than that of DRAM. Furthermore, the write speed was not as fast as that of SRAM. As a result, SRAM/DRAM hierarchy has been used for most of the systems. The challenges for MRAMs are density and speed.

STT MRAMs with perpendicular MTJs were proposed and developed to overcome the challenges. Recently, write current smaller thabt 50 micro-amperes with 2-3 nono-second pulse-width was also demonstrated by using perpendicular MTJ.

Progress on Normally-off memory systems

Systems with MRAM/MRAM can get data very fast and store data very fast. Supply electricity can be turned off very often (even between typing). Normally-off systems which uses MRAM proved 70% reduction of power consumption.

9167-49, Session 9

Perpendicular magnetic tunnel junction material optimization for MRAM cells and spin transfer torque field and bias dependence *(Invited Paper)*

Ricardo C. Sousa, Lea Cuchet, Bernard Rodmacq, Stéphane Auffret, Bernard Dieny, Commissariat à l'Énergie Atomique (France)

Magnetic tunnel junctions with perpendicular magnetic anisotropy are particularly attractive to realize devices of reduced lateral dimension due to their large values of perpendicular anisotropy. This work shows the optimization of bottom and top CoFeB electrodes in perpendicular magnetic tunnel junctions to determine the electrode's "dead layer" and critical thicknesses, where the magnetization anisotropy goes from out-of-plane to in-plane orientation. Magnetic properties are then correlated to transport properties on full-sheet samples with the Current In-Plane Tunneling (CIPT) technique. The optimum magnetic and transport properties are obtained for top FeCoB and bottom CoFeB thicknesses of about 1.5 and 1.2 nm, respectively, for which magnetic layers on both side of the MgO barrier are perfectly perpendicular-to-plane in zero external magnetic field. The critical current for spin transfer torque switching was determined from voltage-field state diagrams using pulses below 100ns. The minimum critical current for enabling both AP to P and P to AP switching by STT can be determined using the phase diagram data. Plotting the transition boundaries corresponding to switching from parallel P to antiparallel AP state, and from AP to P, it can be shown that to a first approximation the critical current density reduces linearly with applied field above a critical pulse voltage. These boundaries cross at a field point where the switching between AP(P) and P(AP) states is possible with the same current density, representing the minimum current density. In this device is found to be 2.9MA/cm^2 at a bias field of 33Oe.

9167-50, Session 9

Materials challenges in perpendicular magnetic tunnel junctions for embedded spin-transfer-torque MRAM *(Invited Paper)*

Kangho Lee, Jimmy Kan, Qualcomm Inc. (United States); Matthias Gottwald, Qualcomm Inc. (Belgium); Chando Park, Seung Kang, Qualcomm Inc. (United States)

Embedded spin-transfer-torque MRAM (STT-MRAM) has tremendous potential to innovate mobile industry, enabling cost-effective and power-efficient mobile chips. In this talk, we will discuss material challenges in optimizing perpendicular magnetic tunnel junctions (pMTJs) for scalable STT-MRAM technology and present the latest results from our full-stack pMTJ films that are suitable for early embedded STT-MRAM products in emerging mobile markets

9167-51, Session 9

Characteristics of orthogonal spin transfer magnetic tunnel junction devices *(Invited Paper)*

Mustafa Pinarbasi, Spin Transfer Technologies, Inc. (United States)

Spin transfer torque magnetic random access memory (STT-MRAM) devices are of great interest for non-volatile memory applications. Most of the effort has been concentrated on collinear magnetic structures where the switching process is stochastic with broad switching times. We will report on the recent results for devices based on the orthogonal spin transfer torque (OST) structures. This structure includes an additional polarizer compared to the standard MTJ structures where the magnetization of the polarizer is perpendicular to the freelayer. Having an orthogonal polarizer provides certain advantages such as instantaneous initiation of the magnetization reversal as a result of large initial spin transfer torque. The processing of such devices, the structure, and switching times will be presented.

9167-52, Session 10

Properties of CoFeB/MgO systems with perpendicular anisotropy *(Invited Paper)*

Jean-Paul Adam, Karin Garcia, Adrien Le Goff, Rémy Soucaille, Capucine Burrowes, Nicolas Vernier, Dafiné Ravelosona, Joo-Von Kim, Thibaut Devolder, Univ. Paris-Sud 11 (France); Stéphane Guilet, Lab. de Photonique et de Nanostructures (France); Berthold Ocker, SINGULUS TECHNOLOGIES AG (Germany)

Magnetic tunnel junctions with ultrathin CoFeB free layers in contact with MgO can exhibit both a Perpendicular Magnetic Anisotropy and a reasonably low damping, which makes them suitable for spin torque applications. However material research is needed to optimize this system. We studied the composition dependence of the magnetic properties of CoFeB free layers with perpendicular anisotropy, the dependence of these properties on the degree of intermixing at a given Ta/CoFeB interface and we have included them in full magnetic tunnel junctions to compare wafer-level to device properties.

Using ferromagnetic resonance and magnetic microscopy, we studied the dependence of the anisotropy and the damping upon the FeCo ratio in both amorphous and crystalline states. The damping increases by 0.001 upon crystallization but vary little with composition on the Fe-rich side, with a minimum of 0.011 in amorphous Co40Fe40B20 film. At high cobalt content, the anisotropy lowers while the damping increases [1]. The domain wall velocities evolve consistently [2].

The degree of intermixing at a CoFeB/Ta interface affects the magnetic properties. It is detrimental to all properties except the anisotropy field since the growth of dead layer at the Ta interface reduces the demagnetizing energy while leaving the interface anisotropy unchanged [3].

Finally we have included our free layers in magnetic tunnel junction nanopillars. The free layer is essentially unaffected by the patterning, apart from the expected coercivity increase. In contrast the Reference layers properties evolve substantially, in particular they loose part of their anisotropy and of their interlayer exchange coupling.

[1] T. Devolder et al., Appl. Phys. Lett., 102, 022407 (2013).

[2] C. Burrowes et al. Appl. Phys. Lett., 103, 182401 (2013).

[3] T. Devolder et al. J. Appl. Phys. 113, 203912 (2013).

9167-53, Session 10

Switching time distributions of orthogonal spin transfer devices at nanosecond time scales *(Invited Paper)*

Georg Wolf, Gabriel D. Chaves-O'Flynn, Andrew D. Kent, New York Univ. (United States); Bartek Kardasz, Spin Transfer Technologies, LLC (United States); Steve Watts, Mustafa Pinarbasi, Spin Transfer Technologies, Inc. (United States)

Spin transfer torque operated magnetic memory cells are promising candidates to replace modern random access memory concepts. In particular, orthogonal spin transfer (OST) devices, formed by a collinear magnetized magnetic tunnel junction (MTJ) and an additional polarizing layer magnetized perpendicular to the free layer of the MTJ, offer certain advantages. Specifically, this type of structure leads to a spin current with an effective angle to the free layer magnetization, which provides a large initial spin torque that can initiate a faster magnetization reversal [1,2]. However, switching is always to some degree a stochastic process, due to thermal fluctuations of the magnetization. It is important to directly determine the switching time and its distribution to assess the impact of fluctuations in spin transfer devices, particularly at short time scales.

We investigate the magnetization reversal of OST devices with time-resolved single shot experiments. A fast real time oscilloscope enables the observation of the magnetization reversal on sub-nanosecond time scales. From the measured time profile of the current flowing through a device in response to an applied voltage pulse we can extract the switching time. Acquiring the respective distribution of the switching time as a function of pulse amplitude gives insight into the interplay of spin torque initiated magnetization reversal and thermal fluctuations. We will contrast these results to those of a purely collinear magnetized device. We will also discuss our micromagnetic simulations of respective structures.

[1] A. D. Kent et al., Appl. Phys. Lett. 84, 3897 (2004).

[2] D. Pinna et al., Phys. Rev. B 88, 104405 (2013).

9167-54, Session 10

Time-resolved magnetization dynamics in perpendicular STT-MRAM devices *(Invited Paper)*

Luc Thomas, Guenole Jan, Son Le, Yuan-Jen Lee, Huanlong Liu, Jian Zhu, Ru-Ying Tong, Keyu Pi, Yu-Jen Wang, Tom X. Zhong, Terry Torng, Po-Kang Wang, Headway Technologies, Inc. (United States)

In this talk, we will discuss current-driven magnetization dynamics in perpendicularly magnetized (PMA) STT-MRAM devices. We have performed time-resolved resistance measurements to probe the behavior of single Magnetic Tunnel Junction (MTJ) devices in response to voltage pulses of varying amplitudes and lengths. We find that the magnetization of these PMA-MTJ devices can be switched reliably with sub-nanosecond long voltage pulses. However, we also find that magnetization dynamics in response to voltage excitations can be more complex than anticipated. We will discuss the different behaviors that we observe depending on the device diameter and the structure of the MTJ stack.

9167-55, Session 10

High-performance computing based on spin-diode logic *(Invited Paper)*

Joseph S. Friedman, Bruce W. Wessels, Northwestern Univ. (United States); Damien Querlioz, Univ. Paris-Sud 11 (France); Alan V. Sahakian, Northwestern Univ. (United States)

The application of spintronics to computing has been impeded by the difficulty in cascading spintronic logic gates. While binary switching in response to a magnetic field has been demonstrated in a variety of materials and devices, the identification of an efficient mechanism for dynamically creating the required magnetic fields has been a confounding challenge. Here we discuss spin-diode logic, a cascaded spintronic logic family in which the current through the logic devices is used to create the controlling magnetic field for other logic devices. This logic family is based on spin-diodes, magnetoresistive devices exhibiting strong switching in response to an applied magnetic field above its characteristic threshold field.

Spin-diode logic, which can be applied to both positive and negative magnetoresistance devices, uses current as the binary state variable. All spin-diodes are connected to constant voltages, and the current through each spin-diode is modulated by the applied magnetic field. This current is used as the source of a magnetic field across another spin-diode in a cascading mechanism that can be extended to large complex circuits. The computing speed is related to the speed of electromagnetic wave propagation rather than the speed of electron motion, providing exceptionally high performance.

An additional paradigm for efficient spintronic computing is based on Bayesian probability. Early results on the spintronic implementation of this non-deterministic system are promising, leveraging the unique characteristics of newly available spintronic devices for non-Von Neumann computing. These novel circuit structures provide an opportunity for spintronics to replace CMOS in general-purpose computing.

9167-56, Session 11

Magnon Hall effect: A theoretical investigation *(Invited Paper)*

Ingrid Mertig, Martin-Luther Univ. Halle-Wittenberg (Germany) and Max-Planck-Institut für Mikrostrukturphysik (Germany); Alexander Mook, Martin-Luther Univ. Halle-Wittenberg (Germany); Juergen Henk, Max-Planck-Institut für Mikrostrukturphysik (Germany)

Ferromagnetic insulators with Dzyaloshinskii-Moriya interaction show the magnon Hall effect (Y. Onose et al, Science 329 (2010) 297), i.e., a transverse heat current upon application of a temperature gradient. Our theoretical investigation is based on semiclassical transport theory, the Berry curvature and a quantum mechanical Heisenberg model. For two-dimensional kagomé lattices, we establish a close connection of the magnon Hall effect with the topology of the magnon dispersion relation. From the calculated topological phase diagram, we predict a change of sign of the transverse thermal conductivity with temperature. The bulk-boundary correspondence is proven by topologically non-trivial edge magnons. Moreover, we provide a figure of merit for the transverse thermal conductivity and compare our results with experimental data for the pyrochlore syste $Lu_2V_2O_7$.

9167-57, Session 11

Various methods of spin current generation and manipulation *(Invited Paper)*

Sadamichi Maekawa, Japan Atomic Energy Agency (Japan)

The flow of electron spin, the so-called “spin current”, is a key concept in the recent progress in spintronics [1,2]. When the spin current interacts with the magnetic moment in a ferromagnetic metal, the angular momentum and energy conservations give rise to the spin transfer torque and spinmotive force, respectively. When it is injected into a non-magnetic metal attached to ferromagnet, the electric current is induced through the spin-charge conversion mechanism (inverse spin Hall effect). The generation and manipulation of the spin current and a variety of novel phenomena given by the spin current, including the spin Seebeck effect and spinmotive force, are discussed [3-6].

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[5] H. Adachi et al., Rept. Prog. Phys. 76, 636501 (2013).

[6] S. Maekawa et al., J. Phys. Soc. Jan. 82, 102002 (2013).

9167-58, Session 11

Anomalous spin and charge Seebeck effect in a quantum well with spin orbit interaction *(Invited Paper)*

Catalina Marinescu, Clemson Univ. (United States); Andrei Manolescu, Reykjavik Univ. (Iceland); Jeremy Capps, Clemson Univ. (United States)

In a semiconductor quantum well with linear Rashba and Dresselhaus spin-orbit interactions of equal strengths, the low temperature ground state obtained in the presence of the Coulomb interaction is shown to correspond to a long-range antiferromagnetic spin alignment. This situation is obtained on account of the opposite-spin single-particle state degeneracy at $mb k = 0$ that makes the spin instability possible. A theory of the resulting magnetic phase is formulated within the Hartree-Fock approximation of the Coulomb interaction by means of a canonical transformation to new quasiparticle states of variable spin orientation, separated by an energy gap that depends on the strength of the spin-orbit coupling and electron density . In the itinerant anti-ferromagnetic phase, we employ a Boltzmann transport formalism to show that scattering on magnetic impurities of the newly created quasiparticles leads to an energetic imbalance that favors the apparition of a large charge and spin thermopower estimated to be up to an order

of magnitude larger than in a regular system. The experimental detection of the anomalous Seebeck effect can be seen therefore as a probe of the ground state magnetization.

9167-59, Session 11

Spin-caloritronics in magnetic nanodevices *(Invited Paper)*

Santiago Serrano-Guisan, International Iberian Nanotechnology Lab. (Portugal); Niklas Liebing, Patryk Krysteczko, Xiukun Hu, Physikalisch-Technische Bundesanstalt (Germany); Karsten Rott, Gunter Reiss, Univ. Bielefeld (Germany); Judith Kimling, Tim Böhnert, Kornelius Nielsch, Univ. Hamburg (Germany); Michael Czerner, Christian Heiliger, Justus-Liebig-Univ. Giessen (Germany); Hans-Werner Schumacher, Physikalisch-Technische Bundesanstalt (Germany)

Spin-caloritronics is a new emerging field of spintronics where thermal gradients developed in nanostructured devices can play an active role to control and manipulate spin-based effects like thermally driven spin currents and heat driven magnetization reversal. Such effects are very promising to improve energy efficiency in future devices as well as to develop novel applications for industry and metrology such as magnetic heat valves. However, to date, many concepts have only theoretical basis and need to be studied experimentally. Moreover, the large current densities involved in spin transfer torque effects in magnetic tunnel junction (MTJ) nanodevices imposes a better knowledge of the interplay of heat, charge and spin currents at such conditions.

Here we will present a compilation of the observed spin-caloric properties in MTJ nanodevices like the large Tunneling Magneto-Seebeck ratios and its angular dependence, the Tunneling Magneto-Thermocurrent and the possibility to explore thermal spin transfer torque effects on magnetization dynamics. We will also discuss the uncertainty of input parameters and its large influence on the calculated temperature profile through the nanostructure (and hence on the derived Seebeck coefficients), and we will show some different approaches to minimize it. Moreover, in order to establish a reliable method to derive Seebeck coefficients different experimental techniques for magneto-thermoelectric measurements in MTJ nanodevices (optical heating, electrical heating and ohmic non-linear correction) will be considered.

Finally magneto-thermoelectric figure of merit ZT studies in metallic magnetic multilayer nanostructures will be presented and the possibility to develop magnetic switchable thermoelectric devices will be addressed.

9167-60, Session 12

Anisotropic magneto-thermal transport: theory and experiments *(Invited Paper)*

Jean-Eric Wegrowe, Do Chung Pham, Henri-Jean Drouhin, Ecole Polytechnique (France); Daniel Lacour, Michel Hehn, Univ. Henri Poincaré Nancy (France)

The anisotropic properties of thermal transport in insulating or conducting ferromagnets are derived on the basis of the Onsager reciprocity relations applied to a magnetic system. It is shown that the angular dependence of the temperature gradient takes the same form as that of the anisotropic magnetoresistance, including anomalous and planar Hall contributions [1].

The experimental study [2] shows that the voltage measured between the extremities of the non-magnetic electrode in thermal contact to the Py or YIG ferromagnetic layers follows the predicted angular dependence. Furthermore, the sign and the amplitude of the magneto-voltaic signal measured is in agreement with the thermocouples calculated from the corresponding Seebeck coefficients, for the three different electrodes used in the study (Pt, Cu, Bi).

[1] J.-E. Wegrowe, H.-J. Drouhin, D. Lacour, “Anisotropic Thermal Transport and Spin-Seebeck effect”, Phys. Rev B in press 2014.

[2] Pham Do Chung, PhD dissertation, Ecole Polytechnique, April 2014

9167-61, Session 12

Spin-dependent thermoelectric transport in magnetoresistive nanowires *(Invited Paper)*

Kornelius Nielsch, Univ. Hamburg (Germany)

The anisotropic magneto-thermal resistance (AMTR) effect is the thermal analogue of the anisotropic magneto-resistance (AMR) effect observed in ferromagnetic conductors. We have investigated the AMTR effect in Ni nanowires. We present measurements of electrical and thermal transport properties of cylindrical Ni nanowires in the temperature range between 78 K and 380 K. The determined AMTR ratios lie below the AMR ratios, resulting in an anisotropic Lorenz number. To explain this observation, we apply a simple model that considers spin mixing due to electron-magnon scattering. In comparison, we will present measurements of the magneto-thermal resistance (AMTR) on GMR Co/Ni multi-layer multilayers under thermal transport in-plane, where a Field-independent Lorenz number over the entire temperature range is observed.

The magneto-thermopower (Seebeck coefficient) is measured and correlated to the anisotropic magneto-resistance of Co-Ni alloyed nanowires. By a micrometer setup, three magneto-thermoelectric quantities are determined along the nanowire in magnetic fields applied perpendicularly to the nanowire axis: temperature difference, thermovoltage and electrical conductivity. The highest absolute and relative variation of the Seebeck coefficient are determined to be 1.5 μVK-1 at RT for Co0.24Ni0.76 nanowires and 10.9 % at 100 K for Ni nanowires. Power factors of 3.7 mW/mK2 have been achieved, which is competitive with common thermoelectric materials like TiS2 and Bi2Te3.

More recent experiments have been performed on the magneto-Seebeck effect on multilayer CoNi/Cu multilayered nanowire, which exhibited the GMR effect. In detail the Mott relation between the magneto-Seebeck effect and the magneto-resistance have been analyzed.

9167-62, Session 12

Probing fundamental physics and materials properties of spincaloritronic systems with suspended thermal platforms *(Invited Paper)*

Barry L. Zink, Univ. of Denver (United States)

Interest in spincaloritronics, the interaction of heat, charge, and spin currents in ferromagnetic (FM) systems, continues to grow. This is driven by potential applications not only in spin current generation for future spintronic circuits, but possible energy-harvesting devices that could use transport in the spin channel to overcome the coupling of thermal and electrical conductivity that has long confounded the search for more efficient thermoelectric materials. However, potential optimization of these effects and eventual applications of spincaloritronic devices is possible only if the fundamental interactions are understood. Furthermore, the effect of materials and interface structure on the resulting spincaloritronic properties must be determined. Our research focuses on advancing this understanding, with a particular emphasis on accurate control and measurement of thermal gradients on the thin films or nanostructures often of greatest interest. Reliable measurements of thermally-driven effects in such samples with tiny thermal mass often require great care. In this talk Prof. Zink will present recent measurements of Peltier, Seebeck, and Nernst effects in FM thin films, made using unique micromachined thermal isolation platforms. These allow “zero substrate” heating of thin films, which eliminates unintended thermal gradients that can often complicate probes of the fundamental physics and materials properties. We will clarify the role of the anomalous Nernst Effect and transverse thermopowers, such as the planar Nernst effect, in FM metals as well as describing early steps toward “zero substrate” experiments on ferromagnetic insulating films. We will also describe

efforts to better understand the nature of the FM/paramagnet interfaces used to detect or convert spin currents in spincaloritronic devices.

This work was performed in collaboration with D. Wesenberg, and A. Hojem, and supported by the NSF CAREER award (DMR-0847796).

9167-63, Session 13

Chiral spin torque at magnetic domain walls *(Keynote Presentation)*

Stuart S. P. Parkin, IBM Research - Almaden (United States)

Spin-polarized currents provide a powerful means of manipulating the magnetization of nanodevices, and give rise to spin transfer torques that can drive magnetic domain walls along nanowires. In ultrathin magnetic wires, domain walls are found to move in the opposite direction to that expected from bulk spin transfer torques, and also at much higher speeds. We show that this is due to two intertwined phenomena, both derived from spin–orbit interactions. By measuring the influence of magnetic fields on current-driven domain-wall motion in perpendicularly magnetized Co/Ni/Co trilayers, we find an internal effective magnetic field acting on each domain wall, the direction of which alternates between successive domain walls [1]. This chiral effective field arises from a Dzyaloshinskii–Moriya interaction at the Co/Pt interfaces and, in concert with spin Hall currents, drives the domain walls in lock-step along the nanowire. Elucidating the mechanism for the manipulation of domain walls in ultrathin magnetic films will enable the development of new families of spintronic devices such as Racetrack Memory [2].

[1] K.-S. Ryu, L. Thomas, S.-H. Yang, S.S.P. Parkin, Nature Nanotechnology 8, 527 (2013).

[2] S.S.P. Parkin et al., Science 320 (2008) 190-194.

9167-64, Session 13

Spin-orbit torques in ferromagnetic heterostructures: fundamentals and applications *(Invited Paper)*

Kevin Garello, Can Onur Avci, ETH Zürich (Switzerland); Mihai Miron, Olivier Boulle, SPINTEC (France); Frank Freimuth, Forschungszentrum Jülich GmbH (Germany); Yuriy Mokrousov, Stefan Blügel, Max-Planck-Institut für Festkörperforschung (Germany) and Forschungszentrum Jülich GmbH (Germany); Gilles Gaudin, SPINTEC (France); Pietro Gambardella, ETH Zürich (Switzerland)

Current-induced spin torques are of great interest to manipulate the orientation of nanomagnets without applying external magnetic fields. Recent demonstrations of perpendicular magnetization switching induced by in-plane current injection in ferromagnetic heterostructures have drawn attention to a class of spin torques based on orbital-to-spin momentum transfer (SOTs), which is alternative to pure spin transfer torque (STT) between noncollinear magnetic layers and amenable to more diversified device functions.

In this talk, we will report on the quantitative vector measurement of SOTs in Pt/Co/AlOx and Ta/CoFeB/MgO trilayers using harmonic analysis of the Hall Voltage as a function of the applied current and magnetization direction. We find that both the field-like and antidamping-like spin-orbit torques are composed of constant and magnetization-dependent contributions revealing a scenario that goes beyond simple models of the spin Hall and Rashba contributions to SOTs. Further, we show that these parameters vary strongly with annealing. Such variations correlate with changes of the saturation magnetization and magnetic anisotropy and are assigned to chemical and structural modifications of the layers.

After describing the main spin-orbit interactions observed in ferromagnetic heterostructures, we will present their straightforward impact on magnetic memory technologies and recent advances to build the first SOT-based perpendicular MRAM device.

9167-65, Session 13

Spin orbit torques and chiral magnetic texture in magnetic heterostructures *(Invited Paper)*

Masamitsu Hayashi, National Institute for Materials Science (Japan)

Spin orbit torques in ultrathin magnetic heterostructures are attracting great interest since it enables magnetization manipulation which is not possible with conventional spin torque devices. We have studied the size and sign of spin orbit torques in ultrathin magnetic heterostructures to reveal the underlying physics of the generation of such torques. Special focus is paid on the torque driven by the spin Hall spin current. Current induced domain nucleation and domain wall motion in related structures will be discussed in connection with the chiral magnetic texture developed in magnetic heterostructures.

Spin orbit torque in these systems can be represented by the “effective magnetic field”, which illustrates the strength and direction of the force exerted on the magnetic moments from the generated spin currents via the spin orbit effects (e.g. the spin Hall effect). We find that the effective field is sensitive to the layer thickness and the material of the heterostructure. The effective field has damping-like and field-like components, similar to those in magnetic tunnel junctions, and the relative size between the two varies with the layer thickness. The size of each component affects the efficiency of magnetization switching and current induced domain wall motion.

For domain wall motion, we find that Neel walls emerge owing to the chiral magnetic exchange interaction that develops at interfaces. The size and sign of such anisotropic exchange interaction, i.e. the Dzyaloshinskii-Moriya interaction, shows significant dependence on the material adjacent to the magnetic layer.

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9167-66, Session 14

New Heusler compounds for spin transfer torque *(Invited Paper)*

Claudia Felser, Daniel Ebke, Max-Planck-Institut für Chemische Physik Fester Stoffe (Germany); Gerhard H. Fecher, Max-Planck-Institut für Chemische Physik Fester Stoffe (Germany) and Johannes Gutenberg Univ. (Germany); Siham Ouardi, Ajaya K. Nayak, Max-Planck-Institut für Chemische Physik Fester Stoffe (Germany)

Heusler compounds are a remarkable class of materials with more than 1,000 members and a wide range of extraordinary multifunctionalities including half-metallic high-temperature ferri- and ferromagnets, multiferroic shape memory alloys, and tunable topological insulators with a high potential for spintronics, energy technologies and magnetocaloric applications. Recent development of efficient spintronic devices is based on the spin transfer torque (STT) phenomenon. In 2007 Mn3-xGa was identified as a potential electrode for STT applications [1,2]. In general tetragonal Heusler compounds Mn2YZ as potential materials for STT and spincaloric applications can be easily designed by positioning the Fermi energy at the van Hove singularity in one of the spin channels. The Mn3+ ions in Mn2YZ cause a Jahn Teller distortion [3]. High calculated magnetic anisotropy energy (MAE) is the sufficient condition for a material with perpendicular magneto-crystalline anisotropy (PMA). Materials with saturation magnetizations (MS) of 0.2 – 4.0 μB, high Curie temperatures (TC) of 380 – 800 K, high spin polarizations, PMA, and required lattice constant matching with MgO can be realized with ferri- or ferromagnetic Heusler-related compounds. Additional properties can be designed in tetragonal Heusler compounds with three magnetic sublattices. Mn2PtGa is a tetragonal Heusler compound with a large exchange bias behavior [4] and Mn2CoAl a spingapless semiconductor [5]. A novel non-collinear tetragonal Mn2RhSn Heusler material undergoes a spin-reorientation transition, induced by a temperature change and suppressed by the external magnetic field. Because of the non-centrosymmetric structure, Dzyaloshinskii-Moriya exchange and magnetic anisotropy, Mn2RhSn is supposed to be a promising candidate for realizing the skyrmion state [6].

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9167-67, Session 14

A simple and highly efficient in-line magnetic domain wall injector *(Invited Paper)*

Timothy Phung, Aakash Pushp, Luc Thomas, Charles T. Rettner, See-Hun Yang, Kwang-Su Ryu, John Baglin, Brian Hughes, Stuart S. P. Parkin, IBM Research - Almaden (United States)

The manipulation of domain walls in magnetic nanowires forms the basis of several promising memory and logic nano-devices. Key to the operation of these devices is the controlled injection of domain walls in nanowires at low power. It is known that the magnetic anisotropy of perpendicularly magnetized nanowires can be tailored to create in-plane magnetized regions, thereby leading to the formation of 90° magnetic boundaries. Here we show that by passing a sequence of uni-polar, nanosecond long current pulses across these boundaries, a series of domain walls can be injected into the nanowires. The creation of these domain walls involves utilizing the spin transfer torque obtained from the currents flowing across the 90° magnetic boundary. Remarkably, we find that the currents needed for this domain wall injection process are at least one hundred times smaller than conventional methods that use local magnetic fields from current injection lines fabricated orthogonal to the nanowires. Moreover, we show that the footprint of in-line injection geometry is significantly smaller than that of conventional injection. We shall lastly unravel the physics behind this novel injection scheme.

9167-68, Session 14

Theory of spin injection from a half-metal at finite temperatures *(Invited Paper)*

Kirill D. Belashchenko, James K. Glasbrenner, Univ. of Nebraska-Lincoln (United States); Aleksander L. Wysocki, Univ. of Nebraska-Lincoln (United States)

Spin injection from a half-metallic electrode in the presence of thermal spin disorder is analyzed using a combination of random matrix theory, spin-diffusion theory, and explicit simulations for the tight-binding s-d model. It is shown that efficient spin injection from a half-metal is possible as long as the effective resistance of the normal metal does not exceed a characteristic value, which does not depend on the resistance of the half-metallic electrode, but is rather controlled by spin-flip scattering at the interface. This condition can be formulated as $alphalesssim l/l^N_{sf}T_c^{-1}$, where $alpha$ is the relative deviation of the magnetization from saturation, l and l^N_{sf} the mean-free path and the spin-diffusion length in the non-magnetic channel, and T_c the transparency of the tunnel barrier at the interface (if present). The general conclusions are confirmed by tight-binding s-d model calculations. A rough estimate suggests that efficient spin injection from true half-metallic ferromagnets into silicon or copper may be possible at room temperature across a transparent interface.

9167-69, Session 14

Synchronous domain wall motion in ferromagnetic nanowires achieved via out-of-plane field pulses *(Invited Paper)*

June-Seo Kim, Johannes Gutenberg Univ. Mainz (Germany) and Technische Univ. Eindhoven (Netherlands); Mohamad-Assaad Mawass, Johannes Gutenberg Univ. Mainz (Germany) and Max-Planck Institut für Intelligente Systeme (Germany); Andre Bisig, Benjamin Krüger, Robert M. Reeve, Tomek Schulz, Felix Büttner, Johannes Gutenberg Univ. Mainz (Germany); Markus Weigand, Hermann Stoll, Max-Planck Institut für Intelligente Systeme (Germany); Jungbum Yoon, Chun-Yeol You, Inha Univ. (Korea, Republic of); Gisela Schütz, Max-Planck Institut für Intelligente Systeme (Germany); Henk J. M. Swagten, Bert Koopmans, Technische Univ. Eindhoven (Netherlands); Stefan Eisebitt, Technische Univ. Berlin (Germany) and Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Mathias Kläui, Johannes Gutenberg Univ. Mainz (Germany)

A wide range of future spintronic memory and logic devices require the ability to carefully control the motion of magnetic domain walls (DWs) [1]. Conventional DW manipulation approaches via in-plane magnetic fields are not suitable for the required synchronous propagation of multiple in-plane magnetized DWs in a single wire, since adjacent walls have opposite spin-orientations and hence move in opposing directions, which leads to a loss of data when the DWs annihilate. An alternative is the use of current driven DW motion, which does facilitate synchronous DW motion, yet requires prohibitively large current densities. Here we demonstrate a radically different DW propagation scheme using out-of-plane field pulses which combines the efficiency of field-induced motion with the ability to move multiple walls synchronously. This is achieved for in-plane magnetized transverse DWs of the same chirality through the application of asymmetric field pulses to a wire which incorporates regularly spaced pinning sites. An analytical model is developed to describe the system which reveals that the force on the DW is independent of the wall orientation but crucially depends on the time derivative of the applied magnetic field. It is therefore possible to tailor the force on the DW by choosing the pulse rise and fall times and by applying asymmetric field pulses achieve net DW motion. This scheme is then analyzed in a realistic geometry via micromagnetic modelling. Finally, the concept is experimentally demonstrated using scanning transmission x-ray microscopy.

[1] S. S. P. Parkin; M. Hayashi and L. Thomas: Science, 320, 190 (2008).

9167-70, Session 14

Correlation between spin structure oscillations and domain wall velocities *(Invited Paper)*

Andre Bisig, IBM Research – Zürich (Switzerland) and Johannes Gutenberg Univ. Mainz (Germany) and Max-Planck Institut für Intelligente Systeme (Germany); Martin Stärk, Univ. Konstanz (Germany); Mohamad-Assaad Mawass, Johannes Gutenberg Univ. Mainz (Germany) and Max-Planck Institut für Intelligente Systeme (Germany); Christoforos Moutafis, Paul Scherrer Institute (Switzerland); Jan Rhensius, Paul Scherrer Institute (Switzerland) and Univ. Konstanz (Germany); Jakoba Heidler, Paul Scherrer Institute (Switzerland); Felix Büttner, Johannes Gutenberg Univ. Mainz (Germany) and Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany) and Technische Univ. Berlin (Germany); Matthias Noske, Markus Weigand, Max-Planck Institut für Intelligente Systeme (Germany); Stefan

Eisebitt, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany) and Technische Univ. Berlin (Germany); Tolek Tyliszczak, Lawrence Berkeley National Lab. (United States); Bartel van Waeyenberge, Univ. Gent (Belgium); Hermann Stoll, Gisela Schütz, Max-Planck Institut für Intelligente Systeme (Germany); Mathias Kläui, Johannes Gutenberg Univ. Mainz (Germany) and Univ. Konstanz (Germany)

Magnetic logic and, in particular, sensing devices based on the motion of magnetic domain walls rely on the precise and deterministic control of the position and the velocity of individual magnetic domain walls along curved nanowires. However, varying domain wall velocities have been predicted to result from intrinsic effects, such as periodic domain wall spin structure transformations above the Walker breakdown and extrinsic effects, such as pinning due to imperfections and defects in the nanowire. We use Scanning Transmission X-ray Microscopy (STXM) to directly and dynamically image the nanoscale domain wall spin structure, which allows us to directly check these predictions. We present first direct experimental visualization of the precessional motion of vortex domain walls even below the Walker breakdown in nanometer sized ferromagnetic rings controlled by rotating magnetic fields. The periodic oscillations of the vortex domain wall velocity are consequences of the interplay between the rotating driving field and the periodically changing domain wall spin structure. In addition, we show that the extrinsic pinning from imperfections in the nanowire only affects slow domain walls and we identify the magnetostatic energy, which scales with the domain wall velocity, as the energy reservoir for the domain wall to overcome the local pinning potentials. Our pump and probe experiment demonstrates precise control of the domain wall position at high domain wall velocities, enabling reliable and reproducible high-speed domain wall manipulation in magnetic logic and sensing devices.

9167-71, Session 14

Kondo physics in nanoscopic metallic non-local spin transport devices *(Invited Paper)*

L. O'Brien, Univ. of Minnesota (United States) and Univ. of Cambridge (United Kingdom); M. J. Erickson, D. Spivak, Univ. of Minnesota (United States); Haile Ambaye, Rick Goyette, Valeria Lauter, Oak Ridge National Lab. (United States); Paul A Crowell, Univ. of Minnesota, Twin Cities (United States); Chris Leighton, Univ. of Minnesota (United States)

Despite the maturity of metallic spintronics there remain large gaps in our understanding of spin transport in metals, particularly with injection of spins across ferromagnetic/non-magnetic (FM/NM) interfaces, and their subsequent diffusion and relaxation. Unresolved issues include the limits of applicability of the Elliott-Yafet spin relaxation mechanism, the influence of defects, surfaces, and interfaces on spin relaxation at nanoscopic dimensions, and the importance of magnetic and spin-orbit scattering. The non-local spin-valve is an enabling device in the study of such problems as, in addition to offering potentially disruptive applications, it allows for the separation of charge and spin currents. One particularly perplexing issue in metallic non-local spin valve devices is the often observed non-monotonicity in the temperature-dependent spin accumulation, where the spin signal actually decreases at low temperatures, in contrast to expectations. In this work, by studying an expanded range of FM/NM combinations (encompassing Ni80Fe20, Ni, Fe, Co, Cu, and Al), we demonstrate that this effect is not a property of a given FM or NM, but rather of the FM/NM pair. The non-monotonicity is in fact strongly correlated with the ability of the FM to form a dilute local magnetic moment in the NM. We show that local moments, formed by FM/NM interdiffusion, suppress the injected spin polarization and diffusion length via a novel manifestation of the Kondo effect, thus explaining all observations associated with the low temperature downturn in spin accumulation. We further show: (a) that this effect can be promoted by thermal annealing, at which point the conventional charge transport Kondo effect can be simultaneously detected in the NM, and (b) that this suppression in spin accumulation can be quenched, even at interfaces that are highly susceptible to the effect, by insertion of a thin non-moment-supporting interlayer. Important implications, potentially even for room temperature devices, will be discussed.

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9167-106, Session PWed

Magnetic field effects and nodal ground states in InP nanowires

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Semiconductor nanowires have attracted great interest in the last decade because of their unique optical, electronic, and spin-dependent properties. They also are among the leading candidates to observe exotic states, such at the Majorana Fermions [1]. In a seemingly trivial situation of a single particle confined in a quantum dot, it was predicted that the valence band ground state with a node is possible and was attributed to the formation of orbital textures [2]. This peculiar behavior, may also be present in wurtzite InP nanowires with diameter less then 10 nm [3]. We have systematically explored the possibility for observing such nodal ground state in various nanowires. The presence of this state modifies the basic optical properties of the nanowire, such as the degree of linear polarization. Here we study the change in these states when an external magnetic field is applied along the nanowire axis. We compare the degrees of spin polarization in wurtzite [0001] and zincblende [111] InP nanowires calculated within a k.p method formulation that describes both crystal phases in a single Hamiltonian [4] and accounts for the applied magnetic field.

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9167-107, Session PWed

Probing Majorana-like states in quantum dots and quantum rings

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Engineering chiral p-wave superconductivity in semiconductor structures offers fascinating ways to obtain and study Majorana modes in a condensed matter context. For example, p-wave superconductivity can be induced in semiconductors with strong Rashba spin-orbit coupling by placing them next to s-wave superconductors and exploiting proximity effects. Here, we theoretically investigate chiral p-wave superconductivity in quantum dots and quantum rings. Using both analytical as well as finite-difference methods we calculate the quasi-particle excitation spectra in these structures and the corresponding excitation amplitudes and charge densities. In the topological regime we can observe the chiral edge modes localized at the boundaries and possessing finite energy in quantum dots and quantum rings. By applying a magnetic field which is expelled from the quantum ring, but which creates a flux that is an odd integer multiple of $\phi\_0/2 = \pi h/e$ Majorana modes, that is, (approximately) degenerate edge modes with zero energy and zero charge density,

become possible in the topological regime. Furthermore, we investigate finite-size effects that split these degenerate edge modes as well as the effect of a magnetic field penetrating into the superconducting region that can under certain circumstances still support edge modes with approximately zero energy and charge.

9167-108, Session PWed

Spin polarization of Co(0001)/graphene junctions from first principles

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Junctions comprised of ferromagnets and nonmagnetic materials are one of the key building blocks in spintronics [1]. With the recent breakthroughs of spin injection in ferromagnet/graphene junctions it is possible to consider spin-based applications that are not limited to magnetoresistive effects [2,3]. However, for critical studies of such structures it is crucial to establish accurate predictive methods that would yield atomically resolved information on interfacial properties. By focusing on Co(0001)/graphene junctions and their electronic structure, we illustrate the inequivalence of different spin polarizations [4]. We show atomically resolved spin polarization maps [4] as a useful approach to assess the relevance of Co(0001)/graphene for different spintronics applications.

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9167-72, Session 15a

New directions for engineering quantum spin states: ultracold atomic gases with optically induced synthetic spin-orbit coupling *(Invited Paper)*

Vito Scarola, Virginia Polytechnic Institute and State Univ. (United States)

Materials with strong spin-orbit coupling offer the potential to explore fundamentally new physics in the context of spintronics, the spin Hall effect, and topological insulators. The viability of these new states of matter in solids is typically difficult to asses because strong disorder and defects complicate identification of delicate quantum states. But recent developments in atomic, molecular, and optical physics have demonstrated the ability to engineer pristine environments to mimic spin orbit coupling found in solids. In this talk I will review experimental and theoretical work on ultracold atomic gases as new routes to exotic forms of strongly correlated quantum degenerate matter. I will discuss, in particular, recent experiments using Raman laser coupling to implement synthetic spin-orbit coupling in ultracold atomic gases. By coupling atomic spin states to momentum using lasers, atoms in gases experience artificial Rashba and Dresselhaus spin-orbit couplings. I will discuss models of extreme limits that explore the interplay of strong interactions and strong spin-orbit coupling. Modeling in our group shows that ultracold atoms can be taken into fascinating new regimes that display exotic new spin states, including helical vortex states and spinor Wigner crystals with fractionally charged excitations. Prospects for engineering spiral spin states using synthetic Dzyaloshinskii-Moriya interactions will also be discussed.

9167-73, Session 15a

Spin control and manipulation in (111) GaAs quantum wells *(Invited Paper)*

Paulo V. Santos, Alberto Hernández-Mínguez, Klaus Biermann, Rudolf Hey, Paul-Drude-Institut für Festkörperelektronik (Germany)

The control of spin dephasing is an essential requirement for quantum information processing using electron spins. Among the different spin scattering processes in III-V semiconductor nanostructures, spin dephasing via the spin-orbit (SO) interaction is a major mechanism limiting the lifetime as well as the transport and manipulation of electron spins. The special symmetry of quantum wells (QWs) grown along the non-conventional crystallographic directions [111] and [110] offer interesting possibilities for the control of SO interaction. In this contribution, we review the spin dynamics in these structures as well as concepts for spin storage, transport and manipulation, which combine the long spin lifetime with the control of the electron orbital motion on a micrometer scale. In particular, by enclosing the electron spins in moving potential dots produced by acoustic waves, it becomes possible to transport spins over several tens of micrometer along the plane of a QW. (110) QWs exhibit long spin lifetimes for spins oriented perpendicular to the QW plane, which persist up to temperatures exceeding 100K. These spins can be transported over tens of micrometer by moving potentials produced by acoustic waves. In (111) QWs, the lifetime of spins with arbitrary orientation can be enhanced to values exceeding 100 ns at low temperature by using a transverse electric field to compensate different contribution to the SO interaction. The compensation mechanism is limited at high temperatures (>50 K) by non-linear terms in electron momentum of the SO interaction. Approaches to overcome this limitation as well as to transport and manipulate spins in these structures will be discussed.

9167-74, Session 15a

Spin-orbit induced currents and g-factors in semiconductor quantum dots *(Invited Paper)*

Andrei Silov, Joost van Bree, Paul M. Koenraad, Technische Univ. Eindhoven (Netherlands); Michael E. Flatté, The Univ. of Iowa (United States)

Spin-correlated orbital currents dramatically modify the magnetic moment of an electron spin in many semiconductors, often enhancing the moment by an order of magnitude over its free-electron value. This modified magnetic moment also controls the spin dynamics in nanostructures, and is usually parameterized in the literature as a shape, size and composition dependent g tensor. Despite the central nature of g tensors to high-speed spin manipulation and spin lifetimes, the spatial structure of the spin-correlated orbital currents that determine these g tensors has not been investigated. We describe the spatial distribution of spin-correlated orbital currents for the lowest-energy electron spin states of a quantum dot at zero magnetic field within an analytically-solvable envelope-function formalism, and show that itinerant currents are extended throughout the quantum dot, peaking about midway out from the center of the dot. The resulting magnetic moment is primarily due to these itinerant currents originating from coherent superpositions of conduction and valence envelope functions, rather than from magnetic moments associated with the Wannier functions of each unit cell. We demonstrate that the correct form of the magnetic moment's value differs greatly from the probability density of the spin. For example, the spin of a quantum dot with g=0 will still evince a local magnetic moment that could interact with localized magnetic systems such as ferromagnets or nuclear moments through the hyperfine interaction.

9167-75, Session 15a

Spin injection and spin-orbit coupling in low-dimensional semiconductor nanostructures *(Invited Paper)*

Sebastian Heedt, Isabel Wehrmann, Thomas Gerster, Forschungszentrum Jülich GmbH (Germany); Paul Wenk, Univ. Regensburg (Germany); Stefan Kettemann, Jacobs Univ. Bremen (Germany); Kamil Sladek, Hilde Hardtdegen, Jürgen Schubert, Andreas Bringer, Natalia Demarina, Detlev Grützmacher, Thomas Schäpers, Forschungszentrum Jülich GmbH (Germany)

Narrow-gap semiconductors with strong spin-orbit coupling represent a natural system for spintronic devices, since they provide the ability for electrical spin-manipulation. Quasi one-dimensional nanostructures made from these materials exhibit a strongly suppressed angular dispersion of the electron momenta, which results in an enhancement of spin coherence. Hence, electrical spin injection and signatures of spin-orbit coupling in electrical transport are studied in epitaxially grown semiconductor nanowires. The creation of nonlocal spin-currents in InN nanowires is demonstrated using ferromagnetic metal injectors and tunnel barriers in order to tailor the interface resistance. Furthermore, weak antilocalization quantum corrections to the conductivity are studied for a large variety of differently doped InAs nanowires, establishing comprehensive control of spin-orbit coupling. On the one hand, spin-orbit coupling can be essentially switched on and off via choosing the desired doping conditions during nanowire growth. On the other hand it is shown to be tunable on-chip via electric gating using high-k dielectrics and top gate electrodes. The Rashba effect related to the charge accumulation layer at the nanowire surface as well as the externally applied electric fields together with the Dresselhaus effect are responsible for the lifting of spin degeneracy. By carefully modeling spin transport in these nanowires, the mechanisms responsible for spin relaxation are understood. Beyond that, confinement is further increased by the formation of quantum dots along the axial direction of the nanowires via top and bottom gates. Thus, the few-electron regime can be accessed and the spin coherence properties are extracted by excited states spin spectroscopy.

9167-76, Session 15a

Spin orbit interaction in semiconductor heterostructures *(Invited Paper)*

Makoto Kohda, Tohoku Univ. (Japan)

The spin-orbit interaction (SOI) induces an effective magnetic field (Beff) for an electron, enabling us to control spin states solely by electrical means. However, the SOI inevitably induces the spin relaxation, disrupting a long spin transport. Such a crucial problem is overcome by employing two different types of SOIs; Rashba and Dresselhaus SOIs. The spin relaxation is completely suppressed when both SOIs are in an equal strength, known as persistent spin helix (PSH) state. As a result, precise control and detection of Beff pave the way for future spintronics and quantum information technology. Here, we experimentally demonstrated fitting-free determination of Beff direction in transport measurement under the coexistence of Rashba and Dresselhaus SOIs. In narrow wires, application of in-plane magnetic field (Bin) modulates the amplitude of magneto-conductance, i.e. weak localization, through the additional spin relaxation induced. Since the anisotropic weak localization depends on the relative angle between Bin and Beff, it enables us to evaluate Beff direction with being independent of model fittings. By applying the proposed method to InGaAs based wire structures, we demonstrated the PSH state as the evidence of Rashba / Dresselhaus SOI ratio to be 1.07 ± 0.04 by controlling the top gate.

9167-77, Session 15b

All optical control of magnetic thin films and nanostructures *(Invited Paper)*

Eric E. Fullerton, Univ. of California, San Diego (United States)

The interplay of light and magnetism has been a topic of interest since the original observations of Faraday and Kerr where magnetic materials affect the light polarization. While these effects have historically been exploited to use light as a probe of magnetic materials there is increasing research on using polarized light to alter or manipulate magnetism. For instance deterministic magnetic switching without any applied magnetic fields using laser pulses of the circular polarized light has been observed for specific ferrimagnetic materials. Here we demonstrate optical control of ferromagnetic materials ranging from magnetic thin films to multilayers and even granular films being explored for ultra-high-density magnetic recording. Our finding shows that optical control of magnetic materials is a much more general phenomenon than previously assumed. These results challenge the current theoretical understanding and will potentially have a major impact on data memory and storage industries via the integration of optical control of ferromagnetic bits.

9167-78, Session 15b

Voltage controlled barriers in tunneling anisotropic magnetoresistance devices *(Invited Paper)*

Georg Schmidt, Martin-Luther-Univ. Halle-Wittenberg (Germany)

We demonstrate that in an organic spin valve with a $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) electrode and a non-magnetic counter electrode voltage pulses can change the resistance by almost two orders of magnitude. Additionally tunneling anisotropic magnetoresistance (TAMR) up to 17% can be observed. Our experiments show that the width and height of the injection barrier between the LSMO and the organic semiconductor are changed by applied voltage pulses. Our observations can be explained by the creation of oxygen vacancies in the LSMO whose spatial distribution can be modified by electric fields. Large reverse voltages can reset the device to its original state.

9167-79, Session 15b

Electric-field modulation of spin-wave phase in yttrium iron garnet film *(Invited Paper)*

Tianyu Liu, The Univ. of Iowa (United States); Xufeng Zhang, Hong Tang, Yale Univ. (United States); Michael E. Flatté, The Univ. of Iowa (United States)

An electric field has been predicted to manipulate the phase of spin waves in yttrium iron garnet (YIG) through the spin-orbit interaction, which couples the electric field with the gradient of the magnetization [1?2]. We have observed an electric-field-dependent phase shift in the propagation of surface spin waves in a YIG waveguide. In addition to the spin-orbit effect there is a first-order magnetoelectric effect on the phase shift caused by the change of the magnetization of the YIG due to the applied electric field. The contributions of the two effects can be distinguished by varying the direction of the electric field relative to the YIG magnetization. This work was supported by DARPA MESO.

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9167-80, Session 15b

Recent progress in III-V based ferromagnetic semiconductors: N-type (In,Fe)As and its heterostructures *(Invited Paper)*

Masaaki Tanaka, Pham Nam Hai, Le Duc Anh, The Univ. of Tokyo (Japan)

Carrier-induced ferromagnetic semiconductors (FMSs) generate much attention from the viewpoint of both fundamental physics and potential device applications. Since FMSs are compatible with existing semiconductor heterostructures, we can apply the band-structure engineering to control the properties of FMSs. The most well-studied FMSs are Mn-doped III-V semiconductors. However, the Mn-based FMSs have unsolved problems: (1) They are all p-type, but there is no reliable n-type Mn-based FMS. (2) There is a controversy on the origin of ferromagnetism (whether it is mediated by holes in an extended valence band or in an impurity band). (3) The Curie temperature (TC) is still much lower than room temperature. (4) The coherency of holes are very weak, making their applications to quantum devices difficult.

Here, we show that by introducing iron (Fe) and donors into InAs, it is possible to fabricate a new FMS that can avoid the major problems in the conventional Mn-based FMSs. We demonstrate that (In,Fe)As doped with electrons is an n-type electron-induced FMS, a missing piece of semiconductor spintronics for decades[1,2]. Furthermore, we demonstrate new phenomena in (In,Fe)As and its hetrerostructures: Novel crystalline anisotropic magnetoresistance with two fold and eight fold symmetry[3], and control of ferromagnetism by strain, quantum confinement, and wavefunction engineering in quantum heterostructures with a (In,Fe)As quantum well[4].

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9167-81, Session 16a

Spin pumping and inverse spin Hall effect in Platinum and other 5d metals: the essential role of spin-current discontinuities at interfaces *(Invited Paper)*

Juan-Carlos Rojas-Sánchez, III-V Lab. (France); Nicolas Reyren, Piotr Laczkowski, III-V Lab. (France) and Ctr. National de la Recherche Scientifique (France); Williams Savero, Univ. Joseph Fourier (France) and CEA-INAC (France); Jean-Philipe Attané, Commissariat à l'Énergie Atomique (France); Cyrile Deranlot, Unité Mixte de Physique CNRS/Thales (France); Serge Gambarelli, INAC/SP2M, CEA-Université Joseph Fourier (France); Matthieu Jamet, Commissariat à l'Énergie Atomique (France); Jean-Marie George, Unité Mixte de Physique CNRS/ Thales (France); Laurent Vila, Commissariat à l'Énergie Atomique (France); Henri Jaffrès, Unité Mixte de Physique CNRS/Thales (France) and Forschungszentrum Jülich GmbH (Germany)

It was recently realized that the spin Hall effect (SHE) can be very useful in the area of spintronics, due to its ability to generate pure spin current from charge current, without the use of any magnetic materials or magnetic field. The maximum conversion factor is given by the spin Hall angle θSHE, which can take rather important values (up to 30% was reported for W). This phenomenon is usually observed in materials with large spin-orbit coupling, either intrinsic (Pt, β-Ta, W, etc.) or induced by heavy impurities (Cu doped with Bi or Ir). To investigate this property, several groups studied the reciprocal effect, the so-called inverse spin Hall effect (ISHE), converting a pure "pumped" spin current into a charge current (measured by voltage detection in an "open circuit").

We focus here on the 5d Pt material. Values published nowadays for θSHE in Pt are scattered over one order of magnitude, with a clear correlation between the spin diffusion length λsf and the θSHE, both quantities being related to the spin-orbit strength or its inverse. We performed measurements of spin pumping in a cavity and measured the resulting ISHE voltage. We propose a model including spin memory loss at the interfaces that may reconcile all the different observations. In particular, we demonstrate consistent values of spin diffusion length (3.4 ± 0.4 nm) and spin Hall angle (0.05 ± 0.01) for Pt in different metallic multilayer systems.

9167-82, Session 16a

Spin-current transfer between YIG and Pt: effects on the dynamical properties *(Invited Paper)*

Olivier Klein, Commissariat à l'Énergie Atomique (France)

Yttrium iron garnet ($Y_3Fe_5O_{12}$), commonly referred as YIG, is the champion material for magneto-optical applications as it holds the highest figure of merit in terms of low propagation loss. This is why YIG is widely used in high-end microwave and optical-communication devices such as filters, tunable oscillators, or non-reciprocal devices. It is also the material of choice for magnonics, an emerging field, which aims at using spin-waves (SW) (or their quanta magnons) to carry and process information and whose development is presently limited by the damping constant of SW. This field has recently received a renewed interest because of the prospect that spin-current transfer from an adjacent layer can partially or even fully compensate the intrinsic losses of the traveling SW beyond the natural decay time. Recently, an attempt of damping compensation by pure current in the YIG|Pt system was reported by Kajiwara et al. [1]. In this talk, we will report on our progress to control electrically the dynamical properties of YIG|Pt. In this respect it is crucial to work with the highest quality nanometer-thick films of epitaxial YIG. It is crucial as it allows an enhancement of the effect of the interface spin-current transfer, which scales as the inverse YIG thickness. It is crucial as it permits nano-patterning of the YIG and thus the engineering of the spin-wave (SW) spectra through spatial confinement or through the formation of a spatially inhomogeneous magnetic ground state.

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9167-83, Session 16a

Phase-sensitive detection of spin pumping via the ac inverse spin Hall effect *(Invited Paper)*

Mathias Weiler, National Institute of Standards and Technology (United States)

An intriguing feature of spintronics is the use of pure spin-currents to manipulate magnetization, e.g., spin-currents can switch magnetization in spin-torque MRAM, a next-generation DRAM alternative. Giant spin-currents via the spin Hall effect greatly expand the technological opportunities. Conversely, a ferromagnet/normal metal junction emits spin-currents under microwave excitation, i.e. spin-pumping. While such spin-currents are modulated at the excitation frequency, there is also a non-linear, rectified component that is commonly detected using the corresponding inverse spin Hall effect (iSHE) dc voltage. However, the ac component should be more conducive for quantitative analysis, as it is up to two orders of magnitude larger and linear. But any device that uses the ac iSHE is also sensitive to inductive signals via Faraday's Law and discrimination of the ac iSHE signal must rely on phase-sensitive measurements. In this talk, I will demonstrate that the inductive signal is actually beneficial for the quantitative analysis of the ac iSHE as it can be exploited as a reference for the magnitude and phase of the spintronic signal. Our experimental results [1] show a large ac iSHE magnitude in agreement with recent theoretical predictions. Furthermore, the phase of the ac iSHE signal for Pt is retarded by 110 degrees relative to what is expected from existent theory.

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9167-84, Session 16b

Attempting nanolocalization of all-optical switching through nano-holes in an Al-mask *(Invited Paper)*

Matteo Savoini, Radboud Univ. Nijmegen (Netherlands); Alexander H Reid, Stanford Institute for Materials and Energy Sciences, SLAC National Accelerator Laboratory (United States); Tianhan Wang, Stanford Institute for Materials and Energy Sciences, SLAC National Accelerator Laboratory (United States) and Department of Materials Science and Engineering, Stanford University (United States); Catherine E Graves, Stanford Institute for Materials and Energy Sciences, SLAC National Accelerator Laboratory (United States) and Department of Applied Physics, Stanford University (United States); Matthias C Hoffmann, Stanford Institute for Materials and Energy Sciences, SLAC National Accelerator Laboratory (United States) and Linac Coherent Light Source, SLAC National Accelerator Laboratory (United States); TianMin Liu, Stanford Institute for Materials and Energy Sciences, SLAC National Accelerator Laboratory (United States) and Department of Physics, Stanford University (United States); Arata Tsukamoto, College of Science and Technology, Nihon University (Japan); Joachim Stöhr, Linac Coherent Light Source, SLAC National Accelerator Laboratory (United States); Hermann Dürr, Stanford Institute for Materials and Energy Sciences, SLAC National Accelerator Laboratory (United States); Andrei Kirilyuk, Alexey V Kimel, Theo Rasing, Radboud Univ. Nijmegen (Netherlands)

The interaction of sub-picosecond laser pulses with magnetically ordered materials has developed into a fascinating research topic in modern magnetism. From the discovery of sub-picosecond demagnetization over a decade ago to the recent demonstration of magnetization reversal by a single 40 fs laser pulse, the manipulation of magnetic order by ultrashort pulses has become a fundamentally challenging topic with a potentially high impact for future spintronics, data storage and manipulation. A fundamental issue to be addressed is the spatial resolution. It is of key relevance both scientifically and technologically to be able to control the magnetization at the sub-micron level.

Here we present our results on the magnetization control at the sub-micron level using different approaches. We can for example show that strongly focusing the illuminating pulsed beam can lead to the totally unexpected formation of structures with distinct topological properties.

Moreover a further reduction of the optically controlled area dimension may be attempted through different methods, namely the patterning of the sample to limit the sample area and/or the use of plasmonic nano-antennas to further confine the laser excitation. Both approaches are beneficial in the all-optical control of the magnetization and new results will be presented. In particular, it is possible to obtain an energy effective and sub-diffraction switching in patterned area by playing with the shape and the illumination conditions; as a result, all-optical switching as small as 40 nm in size has been achieved thanks to the field confining effects of resonant dipolar antennas.

9167-85, Session 16b

Ultrafast spin dynamics in metallic layers and strongly correlated oxides *(Invited Paper)*

Ettore Carpene, Fabio Boschini, Hamoon Hedayat, Claudia Dallera, Ezio Puppin, Politecnico di Milano (Italy)

The spin dynamics triggered by an ultrashort optical excitation can lead to a variety of behaviors depending on the specific spin and electronic structure of the material. In simple metallic and ferromagnetic layers, electron-quasiparticles (phonons and magnons) interactions takes place on the sub-picosecond timescale and demagnetization is established within 100 fs. In half-metals, such as manganites and other correlated oxides, spin dynamics is much slower (100 ps) due to the inhibition of spin-flip processes. The investigation of spin dynamics in these classes of materials help shed light on the specific mechanism of optically-induced demagnetization, that is still controversial. Furthermore, ultrashort light pulses can strongly modify the magnetic anisotropies in ferromagnets. This phenomenon can be exploited as an effective route to control the spin order. Optically-induced reversible switching of the magnetization under simple experimental conditions has been recently demonstrated in thin magnetic films on the 100 picoseconds timescale.

9167-86, Session 16b

Weak-localization and weak antilocalization of surface electrons in topological insulators *(Invited Paper)*

Shun-Qing Shen, Hai-Zhou Lu, The Univ. of Hong Kong (Hong Kong, China)

The electronic transport experiments on topological insulators exhibit a dilemma. A negative cusp in magnetoconductivity is widely believed as a quantum transport signature of the topological surface states, which are immune from localization and exhibit the weak antilocalization. However, the measured conductivity drops logarithmically when lowering temperature, showing a typical feature of the weak localization as in ordinary disordered metals. Here, we present a conductivity formula for massless and massive Dirac fermions as a function of magnetic field and temperature, by taking into account the electron-electron interaction and quantum interference simultaneously. The formula reconciles the dilemma by explicitly clarifying that, the temperature dependence of the conductivity is dominated by the interaction, while the magnetoconductivity is mainly contributed by the quantum interference. The theory paves the road to quantitatively study the transport in topological insulators, and can be extended to other two-dimensional Dirac-like systems, such as graphene, transition metal dichalcogenides, and silicene.

9167-87, Session 16b

Weak antilocalisation in topological insulators with strong spin-orbit scattering *(Invited Paper)*

Dimitrie Culcer, Weizhe Liu, The Univ. of New South Wales (Australia); Pierre Adroguer, Julius-Maximilians-Univ. Würzburg (Germany); Xintao Bi, Univ. of Science and Technology of China (China); Ewelina Hankiewicz, Julius-Maximilians-Univ. Würzburg (Germany)

Topological insulators (TI) have revolutionised our understanding of insulating behaviour. They are insulators in the bulk but conducting along their surfaces, thanks to surface states in which the spin and the charge are strongly coupled by means of the spin-orbit interaction. Much of the recent research on TI focuses on overcoming the transport bottleneck [1], namely the fact that surface state transport is overwhelmed by bulk

transport stemming from unintentional doping. The key to overcoming this bottleneck is identifying unambiguous signatures of surface state transport. This talk will discuss one such signature, which is manifest in the coherent backscattering of electrons in TI. Because of the strong spin-orbit coupling in TI one expects to observe weak antilocalisation rather than weak localisation, meaning that coherent backscattering increases the electrical conductivity [2]. The features of this effect, however, are rather subtle, because in TI the impurities have strong spin-orbit coupling as well, greatly increasing the complexity of the problem [3]. I will show that spin-orbit coupled impurities introduce an additional time scale, which is expected to be shorter than the dephasing time, and the resulting conductivity has a logarithmic dependence on the carrier number density, a behaviour hitherto unknown in 2D electron systems. The result we predict is directly observable experimentally and would provide a smoking gun test of surface transport. Furthermore, I will also discuss the effect of electron-electron interactions on transport in this regime.

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9167-88, Session 17a

Room temperature spin transport in condensed matters induced by spin pumping *(Invited Paper)*

Masashi Shiraishi, Kyoto Univ. (Japan); Yuichiro Ando, Osaka Univ. (Japan)

The first success of spin-pumping-induced transport of pure spin current in p-Si at room temperature (RT) opened a door for realizing RT spin transport in condensed matters by the dynamical approach [1]. We have been investigating transport of pure spin current generated by the spin pumping method in various materials, such as graphene [2], Al [3], n-GaAs [4] and so on. In this presentation, we will mainly introduce results on dynamical spin transport in graphene and n-GaAs, and also discuss a possible spurious signals in spin pumping experiments, which comes from self-induced inverse spin Hall effect of ferromagnet [5]

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9167-89, Session 17a

Tree-magnon splitting controlled by temperature *(Invited Paper)*

Kazuya Ando, Takaharu Tashiro, Saki Matsuura, Keio Univ. (Japan)

The spin-orbit interaction in a solid causes a flow of spins, a spin current, to induce an electric field perpendicular to both the spin polarization and the flow direction of the spin current, which is called the inverse spin Hall effect (ISHE). The ISHE has been crucial for exploring the spin physics of inorganic metals and semiconductors, because it enables simple and versatile detection of spin currents in non-magnetic materials. Here we show that a pure spin current can be produced in a solution-processed conducting polymer by pumping spins through a ferromagnetic resonance in an adjacent magnetic insulator, and that this generates an electric voltage across the polymer film [1]. We demonstrate that the experimental characteristics of the generated voltage are consistent with it being generated through the ISHE in the conducting polymer. In contrast with inorganic materials, the conducting polymer exhibits coexistence of high spin-current to charge-current conversion efficiency and long spin lifetimes. Our discovery opens a route for a new generation of molecular-structure-engineered spintronic devices, which could lead to important advances in plastic spintronics.

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9167-90, Session 17a

Spin pumping and spin-orbit effects in Si and Ge *(Invited Paper)*

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The field of spintronics is based on the manipulation of the spin degree of freedom. It uses the carrier spin angular momentum as a basic functional unit in addition to the charge. By combining charge and spin, a single electronic device could then integrate both logic and memory functions limiting power consumption and speeding up data processing. The first requirement of a semiconductor-based spintronic technology is the efficient electrical injection of spin-polarized carriers from an appropriate contact into the device heterostructure made of Si or Ge (the materials of mainstream microelectronics) at room temperature. In this presentation, we focus on the generation of a sizeable spin population into Si and Ge by spin pumping. Here, spin pumping corresponds to the generation of a pure spin current in the Si or Ge films by exciting the ferromagnetic resonance of an adjacent ferromagnetic electrode made of CoFeB with microwaves. The pure spin current is then detected using spin-orbit based effects. Our aim is to understand the basic mechanisms of spin pumping into Si and Ge as well as the spin-to-charge conversion by inverse spin Hall effect (ISHE, bulk effect) and Rashba effect (interface effect). In particular, the influence of the doping type (n and p) and interface resistance on spin pumping-ISHE measurements in germanium will be discussed. Finally, in both Si and Ge, we investigated the spin-to-charge conversion using interface states exhibiting giant Rashba splitting.

9167-91, Session 17a

Dual-frequency ferromagnetic resonance to measure spin current coupling in multilayers *(Invited Paper)*

Rohan Adur, Chunhui Du, Hailong Wang, Sergei Manuilov, Fengyuan Yang, P. Chris Hammel, Ohio State Unive. (United States)

Spin pumping, the transfer of spin angular momentum from a ferromagnet into an adjacent material as a consequence of the excitation of the magnetization of the ferromagnet, represents an intriguing phenomenon with substantial technological potential. It is widely believed that the mechanism for spin pumping in ferromagnet/nonmagnet bilayers is the exchange interaction between the ferromagnet and nonmagnetic material. We report exponential decay of spin pumping from thin $Y_3Fe_5O_{12}$ films to Pt across insulating barriers. This signature of quantum tunneling through a barrier confirms the role of exchange coupling for spin pumping and reveals its dependence on the characteristics of the barrier material. The efficiency of spin pumping is largely determined by the spin mixing conductance at the FM/NM interface. Our measurements of spin pumping in $Y_3Fe_5O_{12}$ /

Cu/Pt and Y3Fe5O12 /Cu/W trilayers with varying Cu thicknesses reveal that Y3Fe5O12/Cu interface has a very large intrinsic spin mixing conductance; in fact we find that the insertion of the Cu layer between Y3Fe5O12 and W leads to enhanced spin currents relative to Y3Fe5O12 /W.

Scanned probe magnetic resonance is a powerful tool in this context offering high resolution magnetic resonance imaging, localized spin excitation and measurement of spin relaxation/damping in nanoscale. We report on microscopic scanned probe magnetic resonance studies of spin dynamics, and explore the relationships between spin lifetime and transport. This research is supported by the U.S. DOE through Grant No. DE-FG02-03ER46054, by the NSF MRSEC program through Grant No. 0820414 and by the Army Research Office through Grant W911NF0910147.

9167-92, Session 17b

Novel quantum anomalous Hall effect for spintronics *(Invited Paper)*

Xiao Hu, National Institute for Materials Science (Japan)

We propose a new quantum anomalous Hall effect characterized by simultaneous nonzero charge and spin Chern numbers. We show that this state can be realized through a full band engineering using a staggered electric potential, antiferromagnetic exchange field and intrinsic spin-orbit coupling to control the three degrees of freedom: spin, sublattice and valley. With first principles calculation we confirm that one can achieve this new state by inserting a [111] mono-atomic layer of gold (Au) into a Mott insulator LaCrO_3 of perovskite structure and applying an electric field along [111] direction. This material is ideal for spintronics applications, since a finite sample provides a spin-polarized quantized edge current, robust to both nonmagnetic and magnetic defects, with the spin polarization reversible by electric field. The total magnetization is compensated to zero, and thus the system can be considered as a topological half-metallic antiferromagnet.

9167-93, Session 17b

Unconventional superconductivity in topological insulators: in search for Majorana fermions *(Invited Paper)*

Ewelina Hankiewicz, Julius-Maximilians-Univ. Würzburg (Germany)

We consider superconductor(S) /surface state of topological insulator(TI)/ superconductor junctions (S) where the S regime describes the surface state of the TI in the proximity with the s-wave superconductor. The novelty of such S/TI/S junctions originates from the electron spin helicity (locking of the momentum and the spin for a surface of TIs) which leads to both the s-wave singlet and the p-wave triplet pairing on the surface underneath the superconductor. The existence of these two superconducting channels leads to interesting features in transport through these junctions.

In particular we show, within the Bogoliubov-de-Gennes approach, that the superconducting Klein tunneling (passing of helical Cooper's pairs through the barrier without a reflection) and formation of a topological Andreev bound state (ABS) (state of hybridized two Majorana fermions)) occur for the normal incidence where ABS is protected against backscattering. For transport channels different than for the normal incidence, the scattering from the junction barrier generates an energy gap in the spectrum supporting non-topological ABSs.

Due to mixed order parameter, the AC Josepson effect is fractional showing higher odd harmonics.

We conclude that favorable conditions for the observation of the topological ABS is to put a barrier in the normal part of the junction or consider narrow TI links with a small number of open channels close to one.

9167-94, Session 17b

A quantum dot coupled to a topological nanowire: a suitable structure to study Majorana bound states *(Invited Paper)*

Edson Vernek, Univ. de São Paulo (Brazil) and Univ. Federal de Uberlândia (Brazil); Poliana H. Penteado, Univ. de São Paulo (Brazil); Antonio C. Seridonio, Univ. Estadual Paulista (Brazil); José Carlos Egues, Univ. de São Paulo (Brazil)

The search for the so-called Majorana bound states (MBS) in topological superconductor systems [1] have attracted a great deal of effort in the recent years. Despite the recent experimental efforts, a clear-cut signature of the MBS is still lacking [2].

Here we discuss a distinctive geometry from those conventionally used in the experiments realized so far. We consider a system composed of a quantum dot coupled to a topological nanowire and to two normal leads [3]. We show that this system constitutes a suitable setup for the investigation of MBS as it provides unique and robust signatures for these bound states. Owing to the high tunability of quantum dot parameters, we discuss possibilities to tell apart features related to other phenomena such as Andreev bound states, the Kondo effect and disorder from those associated to MBS. By employing a simple spinless Kitaev model for the wire and a non-interacting dot we show that the MBS, predicted to appear at the end of the wire, "leaks" into the quantum dot. More interestingly, the "leaked" MBS remains pinned to the Fermi level of the leads ($varepsilon_F$) as the level of the dot is gated to below or above $varepsilon_F$. This pinning of the MBS has no analogue in other fermionic type of bound states.

To show the robustness of our results against interactions in the dot, we investigate a more complete model. In this case we include the Coulomb interaction in the dot and we model the topological wire as realized via a tight-binding chain that includes Rashba spin-orbit interaction, superconducting proximity affect and an external magnetic field. We show that the leaking of the MBS into the dot and its pinning described previously are preserved for $varepsilon_{dot} > varepsilon_F. Due to the Coulomb blockade phenomena, however, the pinning of the MBS may no longer be observed when the dot is singly occupied ($varepsilon_{dot} < varepsilon_F< varepsilon_{dot}+U$, where U is the Coulomb repulsion energy). The pinning of the MBS in the singly occupied regime can be recovered by increasing the Zeeman splitting in the quantum dot, as the Coulomb blockade phenomena is suppressed.

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9167-95, Session 17b

Direct electrical detection of spin-momentum locking in the topological insulator Bi_2Se_3 *(Invited Paper)*

Connie H. Li, Olaf M. J. van 't Erve, Jeremy T. Robinson, U.S. Naval Research Lab. (United States); Ying Liu, Lian Li, Univ. of Wisconsin-Milwaukee (United States); Berend T. Jonker, U.S. Naval Research Lab. (United States)

Topological insulators (TIs) are a new quantum state of matter characterized by metallic surface states populated by massless Dirac fermions. TIs are expected to exhibit new behaviors and open horizons for science previously inaccessible with "conventional" materials. One of the most striking properties is that of spin-momentum locking -- the spin of the TI surface state lies in-plane, and is locked at right angle to the carrier momentum. An unpolarized charge current should thus create a net spin polarization whose amplitude and orientation are controlled by the charge current. This remarkable property has been anticipated by theory, but never accessed in a simple transport structure. Here we show that a bias current indeed produces a net surface state spin polarization via spin-momentum locking in molecular beam epitaxially grown Bi2Se3 films, and this polarization is directly manifested as a voltage on a ferromagnetic metal contact. This voltage is proportional to the projection of the TI spin polarization onto the contact magnetization, is determined by the direction and magnitude of the bias current, scales inversely with Bi2Se3 film thickness, and its sign is that expected from spin-momentum locking rather than a Rashba effect. Similar data are obtained for structures with two different ferromagnet/tunnel barrier contacts, demonstrating that these behaviors are independent of the details of the detector contact. These results demonstrate direct electrical access to the TI surface state spin system and enable utilization of its remarkable properties for future technological applications.

9167-96, Session 18a

Experimental observation of a large ac-spin Hall effect *(Invited Paper)*

Georg Woltersdorf, Martin-Luther Univ. Halle-Wittenberg (Germany); Christian H. Back, Dahai H. Wei, Martin Obstbaum, Univ. Regensburg (Germany)

In spin electronics the spin degree of freedom is used to transmit and store information. Ideally this occurs without net charge currents in order to avoid energy dissipation due to Joule heating. To this end the ability to create pure spin currents i.e. without net charge transfer is essential. Spin pumping is the most popular approach to generate pure spin currents in metals, semiconductors, graphene, and even organic materials. When the magnetization vector in a ferromagnet (FM) - normal metal (NM) junction is excited the spin pumping effect leads to the injection of pure spin currents in the normal metal. The polarization of this spin current is time dependent and contains a very small dc component. However in contrast to the rather well understood dc component the two orders of magnitude larger ac component has escaped experimental detection so far. Here we show that the large ac component of the spin currents can be detected very efficiently using the inverse spin Hall effect (ISHE). The observed ac-ISHE voltages are one order of magnitude larger than the conventional dc-ISHE measured on the same device. The spectral shape, angular dependence, power scaling behavior, and absolute magnitude of the signals are in line with spin pumping and ISHE effects. Our results demonstrate that FM-NM junctions are very efficient sources of pure spin currents in the GHz frequency.

9167-97, Session 18a

Insight about spin Hall effects from spin pumping *(Invited Paper)*

Axel Hoffmann, Wei Zhang, Argonne National Lab. (United States); Vincent Vlaminck, Univ. San Francisco de Quito (Ecuador) and Argonne National Lab. (United States); John E. Pearson, Samuel D. Bader, Ralu Divan, Argonne National Lab. (United States); Lihui Bai, Paul Hyde, Yongsheng Gui, Can-Ming Hu, Univ. of Manitoba (Canada)

Spin Hall effects intermix spin and charge currents in non-magnetic materials and offer the possibility to generate and detect spin currents without ferromagnets [1]. In order to gain insight into spin Hall effects, spin pumping is especially useful, since it enables the generation of spin currents over large interfaces, and thereby generates spin Hall effect voltages up to mV, which can be used for quantifying the spin Hall angle, which is direct measure of the charge-to-spin (and vice versa) conversion efficiency [2,3]. Furthermore, analyzing the data as a function of normal layer thickness enables the determination of the spin diffusion length independent of possible variations of normal metal resistivity and yields 5.5±0.5 nm for Pd [4] and 1.2±0.5 nm for Pt [5]. Even shorter spin diffusion lengths have been determined for Ir and IrMn. Lastly, using the angular field dependence of the electric voltages allows us to show that the spin current from spin pumping scales as theoretically expected with precession angle even into the non-linear excitation regime [6].

This work was supported at Argonne by U.S. DOE-BES, MSE and at Manitoba by NSERC, CFI, and URGP.

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9167-98, Session 18a

Generation and detection of spin currents in magnetic hybrid structures *(Invited Paper)*

Antonio Azevedo, Obed Alves-Santos, Gabriel A. Fonseca-Guerra, Joaquim B. Mendes, Rafael O. Cunha, Univ. Federal de Pernambuco (Brazil); Roberto L. Rodriguez-Suarez, Pontificia Univ. Católica de Chile (Chile); Sergio M. Rezende, Univ. Federal de Pernambuco (Brazil)

The generation of spin current can be obtained by the spin pumping effect in which a time-varying magnetization pumps spins into a nearby material. It can also be accomplished by means of the spin Seebeck effect in which a heat flow within a ferromagnet can produces a flow of spins. In both effects, the flow of spin occurs with no flow of charge carrier. By taking advantage of the spin Hall effect and its reciprocal, the inverse spin Hall effect, the spin and charge currents can be mutually converted into each other in thin layers of materials with large spin-orbit interaction. In this talk we will briefly review the state of the art in this area as well as will show results in which Permalloy (Py), a ferromagnet, and Ir20Mn40, a high temperature antiferromagnetic metal, can also be used as spin current detectors. In both cases the measurements were carried out in bilayers of FM/Py and FM/IrMn, where FM is the insulator ferrimagnetic yttrium iron garnet (YIG). We also show that a self induced inverse spin Hall effect can be generated in single layers of Permalloy under ferromagnetic resonance condition. All of these results open up new possibilities of the detection of pure spin current.

9167-99, Session 18a

Spin noise spectroscopy in semiconductors: from a billion down to single spins *(Invited Paper)*

Jens Hübner, Hendrik Kuhn, Ramin Dahbashi, J. Wiegand, Fabian Berski, Leibniz Univ. Hannover (Germany); J. G. Lonnemann, Leibniz University Hannover (Germany); Michael Oestreich, Leibniz Univ. Hannover (Germany)

Spin noise spectroscopy (SNS) in semiconductors has matured during the past nine years into a versatile and well developed technique being capable to unveil the intrinsic and unaltered spin dynamics in a wide range of semiconductor systems [1,2]. Originating from atom and quantum optics as a potential true quantum non-demolition (QND) measurement technique, SNS is capable of unearthing the intricate dynamics of free or localized electron and hole spins in semiconductors being eventually coupled to the nuclear spin bath as well. Here, I review the major steps which inspired the success of spin noise spectroscopy in semiconductors and present the most recent extensions into the low-invasive detection regime of the spin dynamics for the two extreme limits of very high and extremely low loss rates of spin decoherence, respectively. On the one hand, merging ultrafast laser spectroscopy with SNS enables the detection of spin noise with picosecond resolution, i.e., with THz bandwidths [3] yielding access to otherwise concealed microscopic electronic processes [4]. On the other hand, we present very

high sensitivity SNS [5] being capable to measure the extremely long spin coherence of single holes enclosed in individual quantum dots venturing a step forward towards true optical QND experiments in semiconductors [6]. In addition, I discuss how higher-order spin noise statistics of, e.g., single charges can give information beyond the linear response regime governed by the fundamental fluctuation-dissipation theorem and thereby possibly shed some light onto the nested coupling between electronic and nuclear spins.

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9167-100, Session 18a

Comparison of spin accumulation from FMR-driven spin pumping and DC spin injection within a single silicon-based MOS heterostructure *(Invited Paper)*

Ezekiel Johnson-Helperin, The Ohio State Univ. (United States)

The use of the spin Hall effect and its inverse to electrically detect and manipulate dynamic spin currents generated via ferromagnetic resonance (FMR) driven spin pumping has enabled the investigation of these dynamically injected currents across a wide variety of ferromagnetic materials. However, while this approach has proven to be an invaluable diagnostic for exploring the spin pumping process it requires strong spin-orbit coupling, thus substantially limiting the materials basis available for the detector/channel material (primarily Pt, W and Ta). As a result, comparison of spin pumping generated spin currents with the large body of work based on DC electrical spin injection in materials such as GaAs and Si is problematic. Here, we report FMR driven spin pumping into a weak spin-orbit channel through the measurement of a spin accumulation voltage in a Si-based metal-oxide-semiconductor (MOS) heterostructure. This alternate experimental approach enables the investigation of dynamic spin pumping in a device geometry that is also compatible with more established DC spin injection techniques, allowing for the first time a direct comparison between FMR and electrically driven spin injection mechanisms.

9167-101, Session 18b

Graphene spintronics: spin injection and proximity effects from first principles *(Invited Paper)*

Igor Zutic, Univ. at Buffalo (United States); Guilherme M. Sipahi, Univ. de São Paulo (Brazil); Predrag Lazic, Institut Ruder Boškovic (Croatia); Roland K. Kawakami, The Ohio State Univ. (United States)

We formulate a computationally-inexpensive model to study spin injection and proximity effects in graphene/ferromagnet junctions. By presenting spin polarization maps, we establish a versatile tool to tailor the desired spin-dependent properties for graphene spintronics which suggest a wealth of opportunities, not limited to magnetically storing and sensing information, but also including processing and transferring information.

9167-102, Session 18b

Valley polarization by optical pumping on MoS_2 monolayer *(Invited Paper)*

Baoli Liu, Gang Wang, Chuanrui Zhu, Institute of Physics (China); L. Bouet, Univ. de Toulouse (France); Bernhard Urbaszek, Institut National des Sciences Appliquées de Toulouse (France); Thierry Amand, Xavier Marie, Univ. de Toulouse (France)

Transition metal dichalcogenides are emerging as promising new materials for applications in electronics andoptoelectronics.In particular, monolayer molybdenum disulfide (MoS2) has recently received significant attention experimentally. In contrast to graphene, monolayer(ML) MoS2 has a direct band gap in the visible regionof the optical spectrum and a unique coupling of carrier spin andk-space valley physics due to combined effect of inversion symmetry breakingand the spin-orbitinteraction. The circular polarizationof the absorbed or emitted photon can be directly associatedwith selective carrier excitation in one of the two non-equivalent K valleys (K+ or K—, respectively).

In this presentation, we demonstrate experimentally that valley polarization can be created by circularly polarized light excitation on MoS2 monolayer.The circular polarization of photoluminescence (PL) reaches valus up to 50% polarization at room temperature[1,2]. The measurement of PL polarizationwith transverse magnetic fields up to 9 T shows that the valley-index excitation is robust [2]. Finally, we present the investigation of the effect of uniaxial tensile strain on the valley polarization of monolayer and bilayer MoS2 at room temperature [3]. The polarization decreases with increasing strain for both monolayer and bilayer MoS2.These results shed light on the band structure of MoS2 nanostructures.

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9167-103, Session 18b

Spin dynamics in bilayer graphene, MoS2, and cold atoms *(Invited Paper)*

Ming-Wei Wu, Univ. of Science and Technology of China (China)

No abstract available

9167-104, Session 18b

Charge and spin transport across graphene-ferromagnet junctions *(Invited Paper)*

Enrique Cobas, Adam L. Friedman, Olaf M. J. van 't Erve, Jeremy T. Robinson, Berend T. Jonker, U.S. Naval Research Lab. (United States)

We present experimental measurements of vertical charge and spin transport at graphene/ferromagnetic metal (FM) junctions[1]. The combination of the spin-resolved band structure of certain ferromagnetic metal surfaces with the peculiar band structure of graphene has been predicted to make graphene a tunnel barrier for majority-spin carriers[2,3]. This spin-filtering phenomenon enables highly spin-polarized charge currents with low impedance, an effect that could be a boon to spintronics technology including novel spin-transfer torque (STT) non-volatile memory. Using scalable large-area synthesis and fabrication techniques, we fabricate arrays of FM/Graphene/FM junctions using 1-5 layers of graphene. We find low interface impedance and significant negative magnetoresistance even at room temperature, indicative of the predicted spin-filtering phenomenon. Charge and spin transport across these junctions is examined as a function of applied bias, applied magnetic field and temperature.

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9167-105, Session 18b

Gap opening in zigzag graphene nanoribbons: direct experimental determination of the onset of spin-spin interactions of edge states *(Invited Paper)*

Lian Li, Univ. of Wisconsin-Milwaukee (United States)

Graphene nanoribbons (GNR) have been explored extensively for bandgap engineering, arising from quantum confinement for ribbons with armchair edges, and spin-spin interactions for zigzag edges. In both cases, many-body e-e interactions have been predicted to increase the gap to well above 1 eV for NRs of a few nms, attractive for practical applications. However, its experimental realization remains elusive, particularly the key parameter of many-body effect correction is still untested experimentally. This is largely due to challenges synthesizing zigzag graphene nanoribbons (ZGNR) just a few nm in width. Here, we synthesize ZGNR using Fe nanoparticle-assisted H etching of epitaxial graphene/SiC(0001) in ultrahigh vacuum, which produces monolayer thick NR as narrow as 1 nm for the investigation of width-dependent bandgaps. Using in situ spatially resolved tunneling spectroscopy, we determine a critical threshold of 3 nm, above which width-independent gaps of up to 0.50 eV are found. Below which, however, we find a tunable gap that scales with ribbon width, with a gap of 1.64 eV found for a 1.1 nm ribbon, the largest measured to date for ZGNR. These results provide the first direct experimental confirmation of the spin-spin interactions in gap opening in ZGNR, and reveal a critical width of 3 nm for its onset, and demonstrate that a practical and tunable bandgap can indeed be realized in ZGNRs, albeit a very narrow width must first be achieved.

Conference 9168: Carbon Nanotubes, Graphene, and Associated Devices VII

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9168-1, Session 1

Biomimetic multi-length scale manufacturing in carbon *(Invited Paper)*

Marc J. Madou, Univ. of California, Irvine (United States)

Carbon micro- and nanofabrication techniques (C-MEMS and C-NEMS) are based on the pyrolysis of patterned polymers at different temperatures and in different ambient atmospheres. Carbon, because it is brittle and hard, is a difficult material to machine, polymers on the other hand can be machined easily in a wide variety of machine tools and as a consequence shapes and sizes that are difficult to achieve directly in carbon can easily be made by patterning a polymer first and then converting it to carbon. The C-MEMS and C-NEMS applications we are highlighting in this presentation are ultrasensitive carbon interdigitated arrays (IDA) for nanoelectrochemistry and suspended carbon nano-wires for sensor application in the liquid and gas phase.

9168-2, Session 1

Characterization of plasmon propagation in graphene on PZT substrates via infrared nano-imaging

Michael D. Goldflam, Univ. of California, San Diego (United States); Guangxin Ni, Univ. of California, San Diego (United States) and National Univ. of Singapore (Singapore); Zhe Fei, Alexander S. McLeod, Univ. of California, San Diego (United States); Barbaros Özyilmaz, Antonio H. Castro Neto, National Univ. of Singapore (Singapore); Michael M. Fogler, Dmitri N. Basov, Univ. of California, San Diego (United States)

Using scattering-type scanning near-field optical microscopy (s-SNOM), we have characterized graphene plasmons on a graphene-lead zirconate titanate (PZT) back-gated structure. By applying modest back-gate voltages of ±1 V across the PZT, we have been able to induce variations in the graphene plasmon wavelength of more than ~200 nm. The change in plasmon wavelength we observe corresponds to a shift in carrier concentration in the graphene by more than one order of magnitude. Additionally, we describe the plasmonic losses originating from the presence of PZT in such a device. Our results also suggest that persistent tuning of the graphene plasmon may be achieved by utilizing the ferroelectric nature of PZT.

9168-3, Session 1

Optical impedance transformer for transparent conducting electrodes

Ken X. Wang, Stanford Univ. (United States); Jessica R. Piper, Stanford University (United States); Shanhui Fan, Stanford Univ. (United States)

A fundamental limitation in TCE is thought to be the trade-off between photonic and electrical performances. In this paper, we show that one can improve the photonic performance by optical engineering, without compromising the electrical performance. Specifically, broadband and omnidirectional absorption suppression can be achieved in a TCE embedded in high refractive index dielectric cladding layers with nanostructured antireflection coatings. The scheme acts effectively as an optical impedance transformer.

The first element of the strategy is to suppress the optical absorption in the graphene layers by high index cladding layers. We discuss two configurations. In the first configuration, the graphene layers are embedded in the high index background that fills the entire space. Due to the negligible thickness of the graphene layers, the electromagnetic field approaches its static limit, and the average electric field intensity in graphene is equal to that in the background. For the same incident intensity, the electric field is weaker in a higher-index material. As a result, the absorption coefficient in each graphene layer is $pi alpha / n$. Multiple graphene layers would absorb multiples of $pi alpha / n$. In the second configuration, only the half-space below the graphene layers is filled with the same dielectric material. The absorption coefficient in each graphene layer is $pi alpha [2/(1+n)^2]$.

The second element of the strategy is to achieve antireflection. In the first strategy, we sandwich the graphene layers between the substrate and superstrate layers. Since a higher refractive index of the substrate and superstrate materials is desirable for maximal suppression of absorption in graphene, there would be significant reflection at the superstrate-air interface. Tapering of nanostructures, which provides a graded index for optical impedance matching, has proven to be an effective antireflection strategy. For the antireflection to be optimal, the periodicity of the nanopyramid lattice needs to be smaller than the wavelength of incident light, and the height of the nanopyramid needs to large enough for a gradual index transition. Satisfying these two requirements should result in strong suppression of reflection over broad ranges of both wavelengths and incident angles.

Combining the physics of those two elements, we could construct structures with extraordinarily high transmission. We compare the performance of the optical impedance transformer structure to graphene layers suspended in air and on a substrate.

9168-4, Session 1

Microwave impedance microscopy (MIM) of aligned single walled carbon nanotubes: imaging electronic nanotube character at the nanoscale

Eric Seabron, Scott MacLaren, Univ. of Illinois (United States); Slava V. Rotkin, Lehigh Univ. (United States); William L. Wilson, Univ. of Illinois (United States)

For the last fifty years the electrical engineering community has driven integrated circuit technology to unimagined heights, shrinking silicon transistors, lowering the cost and power requirements of the building blocks for all computation. As transistor technology approach fundamental barriers, Single Walled Carbon Nanotubes (SWCNT) has emerged as one material option for producing the next generation high performance nanoscale transistors. For aligned SWCNT on quartz substrates, emergent device applications require arrays of purely semiconducting SWCNTs at high densities. Over the past three years there have been many breakthroughs in the processing of CNTs for electronic devices spanning densification, doping, and purification. However, in order to advance this process research a reliable inspection technique must be developed. We show that Microwave Impedance Microscopy (MIM) has the capability of mapping an individual nanotube's electrical properties with nanoscale (<50nm) resolution. We show that MIM images can be analyzed to give important quantitative and qualitative information about the aligned CNT arrays without any sample modification. We present a theoretical model of the nanoprobe – nanotube interaction which will allows us to qualitatively correlate tube electronic properties; this may give us insight into chirality driven growth dynamics and help us verify the effectiveness of various purification methods.

9168-5, Session 1

Mapping charge transport in chirality-selected carbon nanotube networks by electroluminescence and Raman microscopy

Florian Jakubka, Stefan B. Grimm, Stefan P. Schiessl, Florentina Gannott, Jana Zaumseil, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Field-effect transistors (FETs) based on networks of semiconducting single-walled carbon nanotubes (s-SWNT) are promising building blocks for flexible electronics. Within random and semi-aligned networks of s-SWNT the current paths are likely to be non-homogeneous depending on network density, diameter distribution and connectivity. Here we introduce two techniques to effectively map and visualize current paths and charge density distribution within the FET channel: 1) near-infrared electroluminescence (EL) from ambipolar s-SWNT network FETs and 2) in-situ confocal Raman microscopy on electrolyte-gated transistors,

We use networks of s-SWNT containing only certain chiralities, e.g., (7,5) or (10,5) nanotubes, which were extracted by dispersion with the conjugated polymer poly(9,9-dioctylfluorene) and other polyfluorene copolymers. Top-gate FETs produced with spincoated films of these s-SWNT show balanced ambipolar transport and efficient near-infrared electroluminescence. Mapping the emission from these networks during a gate voltage sweep allows us to visualize preferential current paths that depend on the source-drain electrode assignment and density of the nanotubes. Furthermore, it is possible to map the distribution of charges within an electrolyte-gated FET based on s-SWNT networks by confocal Raman microscopy. The G'-peak position of the nanotubes shifts linearly with applied gate voltage and thus charge carrier density. This allows us to map the carrier distribution in an operating FET with a spatial resolution of 300 nm. These maps reveal a strong dependence of carrier distribution on network density and source-drain bias.

9168-13, Session 1

Nonlinear optical and electrical conductivity properties of carbon nanotubes (CNT) doped in sol-gel matrices

Mariana Pokrass, Soreq Nuclear Research Ctr. (Israel) and Tel Aviv Univ. (Israel); Zeev Burshtein, Ben-Gurion Univ. of the Negev (Israel); Galit Bar, Applied Physics Division, Soreq (Israel); Raz Gvishi, Soreq Nuclear Research Ctr. (Israel)

Carbon-nanotubes (CNTs) are fascinating compounds, exhibiting exceptional electrical and thermal conductivities, mechanical strength, and non-linear optical (NLO) properties. Their unique structures create large Pi-Pi* electronic clouds. The energy level schemes thus created allow many electronic transitions between the ground and the excited states. In this work, we present a study of non-linear optical and electrical conductivity properties of CNT–doped hybrid organic-inorganic glass composites prepared by a Fast-Sol-Gel method. These composite glasses solidify without shrinkage or formation of cracks, and present promising properties as optical media.

The CNT composite glasses present enhanced absorption at 532 nm, and saturable absorption at 1064 nm. The enhanced absorption at 532 was attributed to 2-photon absorption; saturable absorption was attributed to depletion of the absorbing ground-state, and was analyzed using the modified Frantz-Nodvik equation. Absorption cross-sections were extracted for saturable absorption phenomenon. Such CNT composites glasses may be used as "optical limiting" filters near 532 nm, or as saturable absorbing filters for passive Q-switching of short-pulsed lasers near 1064 nm.

The CNT composites conductivity was studied as a function of the CNT concentration. The electrical properties were interpreted using percolation theory. The maximal measured conductivity was 0.001 (1/?cm) for the CNT composites, representing a conductivity increase of at least 12 orders of magnitude compared to that of pure silica. A low percolation threshold of 0.22 wt.% CNT was obtained. Electrostatic Force Microscopy (EFM) and Conductive mode Atomic Force Microscopy (C-AFM) studies exhibited conductivity at the micro-level, which was attributed to the CNTs dispersion mode inside the matrix.

9168-6, Session 2

Electronics and optoelectronics based on carbon nanomaterial heterostructures *(Invited Paper)*

Mark C. Hersam, Northwestern Univ. (United States)

Improvements in carbon nanomaterial monodispersity have yielded corresponding enhancements in the performance of electronic, optoelectronic, sensing, and energy technologies. However, in all of these cases, carbon nanomaterials are just one of many materials that are employed, suggesting that further device improvements can be achieved by focusing on the integration of disparate nanomaterials into heterostructures with well-defined interfaces. For example, organic self-assembled monolayers on graphene act as effective seeding layers for atomic layer deposited (ALD) dielectrics, resulting in metal-oxide-graphene capacitors with wafer-scale reliability and uniformity comparable to ALD dielectrics on silicon. Similarly, the traditional trade-off between on/off ratio and mobility in semiconducting carbon nanotube (CNT) thin-film transistors (TFTs) is overcome by replacing conventional inorganic gate dielectrics with hybrid organic-inorganic self-assembled nanodielectrics, yielding on/off ratios approaching 10^6 while concurrently achieving mobilities of ~150 cm^2/V-s. Finally, p-type semiconducting CNT thin films are integrated with n-type single-layer MoS2 to form p-n heterojunction diodes. The atomically thin nature of single-layer MoS2 implies that an applied gate bias can electrostatically modulate both sides of the p-n heterojunction concurrently, thereby providing 5 orders of magnitude gate-tunability over the diode rectification ratio in addition to unprecedented anti-ambipolar behavior when operated as a three-terminal device. Furthermore, these CNT/MoS2 p-n heterojunctions show a strong photocurrent response, whose spectral characteristics can be tuned by an applied gate potential. Overall, this work establishes that carbon nanomaterial applications can be substantially enhanced and diversified into new areas through precise integration into heterostructure devices.

9168-7, Session 2

Femtomolar molecular detection with CNT based SERS substrate *(Invited Paper)*

Ali Ozhan Altun, ETH Zürich (Switzerland); Tiziana C. Bond, Lawrence Livermore National Lab. (United States); Hyung Gyu Park, ETH Zürich (Switzerland)

A metal/dielectric/vertically aligned CNT sandwich structure is fabricated for chemical and biomolecular detection using the science of surface enhanced Raman spectroscopy (SERS). High sensitivity is accomplished with the insertion of a nanolayer in between plasmonic metal (gold) and the metallic wire template (multiwalled carbon nanotubes (CNT)). The rational design is twofold: (i) inserting of a screening material against electron transfer between gold and CNT to prevent otherwise quenched local surface plasmon resonance; and (ii) creating a "kissing nanowire" effect to the gold-hafnia-CNT nanowires to enahnce the SERS-based, chem-biodetection sensitivity. Experiments verified appropriateness of our nanoarchitecture design rules by demonstrating femtomolar detection of BPE (1,2 bis-(4-pyridyl)-ethylene) with the hafnium oxide insert layer. This outstanding results of ultrahigh sensitivity as well as CNT-surface plasmon coupling motivated us to pursue a systematic study to gain a deeper understanding on this optoelectronic phenomenon. There are two possible theories to explain the surface plasmon quenching: energy loss (i) through electron transfer and (ii) through dipole-dipole coupling of the fields. If electron transfer is the mechanism, insertion of a dielectric intermediary which provides a Schottky barrier higher than the surface plasmon energy level will eliminate this energy loss. If field coupling is the concern, increasing the dielectric constant of the intermediary will shield the electric fields associated with the surface plasmon dipoles. We have performed a set of experiments to answer these questions by observing the effects of Schottky barrier and dielectric constant on SERS signal by applying different material insertions between gold and CNT.

9168-8, Session 2

Atomically thin optoelectronics: the ideal semi-metal and the insurmountable insulator

Nathaniel M. Gabor, Univ. of California, Riverside (United States)

Graphene, an atomically thin sheet of hexagonally oriented carbon, is a zero band gap conductor (semi-metal) that exhibits extraordinary electronic behavior and broadband optical absorption. Hexagonal boron nitride, which shares a similar structure to that of graphene, is a highly insulating electronic material that does not absorb any light in the visible spectrum. By combining graphene and boron nitride into ultrathin vertical stacks, we can fabricate new optoelectronic devices that demonstrate highly sensitive optical response, yet are only as thick as the width of a DNA molecule. In this talk, I will discuss how stacking these atomically thin materials allows us to explore new types of optoelectronic devices: 1) lateral devices that reveal a novel hot carrier transport regime [Science 344, p.648 (2011)], and 2) interlayer devices which exhibit hot carrier photo-thermal up conversion [submitted Nature Nanotechnology], both of which may lead to more efficient energy harvesting technologies.

9168-9, Session 2

Graphene nanoobjects (GNOs) tailored by interference lithography

Alireza Kazemi, Xiang He, Javad Ghasemi, Seyed Hamidreza Alaie, Noel M. Dawson, Brianna Klein, Terefe Habteyes, Steven R. J. Brueck, Sanjay Krishna, The Univ. of New Mexico (United States)

Graphene nano-objects (GNOs) are nanometer-sized fragments of graphene that show unique optical and electronic properties (e.g. band gap opening and exiton confinement), which make them interesting candidates for a whole range of new applications. These small graphene fragments can have different forms such as graphene nanoribbons (GNRs), graphene nanomesh (GNM) and graphene quantum dots (GQDs).

In this work, we present a facile approach to fabricate GNOs using interference lithography (IL) which is a very low-cost, reliable and scalable technology for the fabrication of nanoscale periodic patterns over large areas. Periodic photoresist (PR) lines and hole arrays were patterned on a monolayer graphene by IL, and used as an etch mask for making GNRs and GNM, respectively.

First a monolayer CVD graphene (on 285 nm Sio2/silicon substrate) was patterned with a 100 nm photoresist (PR) lines with a period of 300 nm, and an O2 plasma was performed to reduce the PR linewidth to ~ 20 nm. After washing the PR lines, an array of uniform GNRs were left on the substrate.

To make GNM, photoresist hole arrays were patterned on a monolayer graphene with a period of 300 nm and diameter of 200 nm. After performing O2 plasma, the PR width was reduced to ~ 20 nm. Following the PR removal, a very uniform GNM was obtained.

The fabricated GNRs and GNM were then used as a channel for a field effect transistor (FET), and optical and electrical characterizations were performed.

9168-32, Session 2

Formation of Fabry-Perot cavity in one-dimensional and two-dimensional GaAs nanostructures

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We report formation of optical cavity and observation of Fabry-Perot resonance in GaAs nanowires and nanosheet grown by metal organic chemical vapor deposition (MOCVD) method with selective area growth (SAG). These nanostructures are grown on (111)B. The formation of cavity in nanowires and nanosheets are fundamentally different. While in nanowires optical cavity is formed along the wire with ends of the wire behaving as mirrors, the three non-parallel edges of GaAs nanosheets are involved in trapping the light. We show that through surface passivation and local field enhancement, both the PL intensity and hence Fabry-Perot peak intensity increases significantly. Transferring the GaAs nanowires and nanosheet on gold substrates (instead of Si/SiO2 substrate) leads to substantial enhancement in the PL intensity (5X) and 3.7X to infinite enhancement of FP peaks. In order to reduce the non-radiative recombination in these nanowires the surface states in the nanowires can be passivated by either an ionic liquid (EMIM-TFSI) or an AlGaAs surface layer. Both forms of passivations lead to enhancement of optical response up to 12X.

9168-10, Session PWed

Separation of the semiconducting and the metallic types of single-wall carbon nanotube by electrophoresis method

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This study was to separate the semiconducting and the metallic types of single-wall carbon nanotubes (SWNTs) by electrophoresis method with the different dispersants that are DNA, Triton X-100 and sodium dodecyl sulfate (SDS), respectively. The dispersants can modify the surface of SWNTs and disperse in the DNA free water or deionised water. As a result of the conductive electricity of m-SWNT (Metallic SWNT) is higher than s-SWNT (Semiconducting SWNT), m-SWNT is very suitable to apply on the flexible substrate coating of transparent conductive film. However, the different dispersants such as DNA, Triton X-100 and SDS coated on SWNTs have different polarity of electronic field. Hence, the different power of electrophoresis was applied to separate out s-SWNT and m-SWNT from the hybrid SWNT. In addition, the DNA nucleic acid fragments length and quantitative can be determine with electrophoresis method. The electrophoresis method is a low cost, low energy required and efficientibility for this fabrication. DNA's nonspecific binding to SWNT wall has been visualized by high resolution transmission electron microscopy. The results of Raman spectrum can verify the separation efficiency and determine the electrical of the samples with the radial breathing mode (RBM, 100-400cm-1) of SWNT. After the dispersion process with DNA, a new peak (~1450 cm-1) has been observed between D-band (~1350cm-1) and G-band (~1550cm-1) that also can identify s-SWNT and m-SWNT. At same time, Fourier transform infrared spectroscopy (FTIR) was used to identify function group for dispersant with SWNT.

9168-25, Session PWed

Fabrication and characterization of 3D gaphene composited metal oxide for energy storage device

Duyoung Choi, Cihan Kurua, Serdar Yavuz, Sungho Jin, Univ. of California, San Diego (United States)

Supercapacitors represent energy storage devices that have attracted increasing attention because of a number of important features including high power density, fast charging/discharging rate, and excellent cycle stability. Typically, carbon based materials are good electrodes for capacitors while transition metal oxides and electrically conducting polymers are good candidates for pseudocapacitors. Among the different electrode materials, graphene attracted a significant attention due to their good conductivity, mechanical flexibility, and stable electrochemical behavior. In comparison, MnO2 is one of the thoroughly investigated transition metal oxides for pseudocapacitors due to its high theoretical specific capacitance (1370 F/g), relatively low cost, and environmental friendliness. However, the theoretical capacitance of MnO2 has rarely been achieved in experiments, mainly due to its poor electrical conductivity (10-5~10-6 S/cm). In order to obtain a high specific capacitance from MnO2, many studies have been conducted, most of which are based on incorporating MnO2 with conductive materials and forming hybrid electrode structures. Such outstanding properties make them promising in a wide range of applications from hybrid vehicles and portable electronics to military devices, where high power density and long cycle-life are highly desirable. In this work, we demonstrate a successful fabrication of scalable 3D MnO2-graphene hybrid electrodes. The electrochemical performances of such 3D hybrid electrodes have been investigated for supercapacitors in a three-electrode system at room temperature, and their structures and properties are described.

9168-26, Session PWed

Ab-initio analysis of carbon nanotube based ammonia gas sensor

Anurag Srivastava, Vikash Sharma, Kamalpreet Kaur, Indian Institute of Information Technology and Management (India); Rajeev Ahuja, Uppsala Univ. (Sweden); Vepa K. Rao, Defence Research & Development Establishment (India)

An ab-initio study has been performed for the analysis of ammonia gas sensing of Carbon Nanotube. The computation has been performed using generalized gradient approximation (GGA) parameterized with Revised Perdew Burke Ernzerhoff (RPBE) type. The electronic property analyses shows that as the single ammonia molecule comes into the contact of the surface of CNT, the metallicity of CNT decreases substantially.The further increases in the number of ammonia molecules in the environment, the metallic nature of CNT changes to semiconducting. Thus, metallic to semiconducting transition confirms the presence of ammonia near to CNT surface.

9168-27, Session PWed

Solar powered UAV using graphene supercapacitors capable of 24/7 flight

Charles Welch, Daniel Roseguo, James Chavez, Daneilla Alvarez, Art Lomibao, Sean Matthews, California State Polytechnic Univ., Pomona (United States)

Solar planes have never been a practical concept due to the high weight and long charge time of batteries. Along with that, solar panels have not been able to effectively provide enough power to sustain long duration flight. Our project plans to provide an optimum integration of solar technology and graphene energy storage to meet the task of flying continuously throughout the night. Due to graphenes amazing physical characteristics, we can provide a low weight, low charge time, high storage supercapacitor, that can adequately use solar charging to the utmost efficiency. The supercapacitors used in this project were designed and invented by the team lead and are a unique and functional solution for energy storage. Using these newly designed supercapacitors, our team was able to cut the battery weight of our UAV in half, and still provide enough power storage to fly continuously through the night. Along with that, the complete design of this aircraft including the flight control system, solar panel integration, circuit design, and flight design is a benchmark for the integration of solar technology for flight. Overall we hope the research from our project can lead the way for integration of graphene supercapacitors in solar technology.

9168-28, Session PWed

Thermal dissipation of photonic crystal defect cavity by the single-layer graphene

Min-Hsiung Shih, Academia Sinica (Taiwan)

Graphene, a two-dimensional material composed of carbon atoms arranged in a hexagonal lattice, which exhibits excellent thermal conductivity, is a potential heat dissipation medium for compact optoelectronic devices. In the meanwhile, photonic crystal cavities have become a promising technology for creating compact and efficient light sources in dense chip-scale optical systems. Most photonic crystal cavities are implanted in suspended membrane structures (air-dielectric-air) to achieve improved vertical optical confinement in the minute cavity. However, thermal accumulation is a critical problem when optical energy is localized within a sub-micrometers region. In this study, single-layer graphene (SLG) grown by chemical vapor deposition (CVD) is used to cover the surface of a photonic crystal (PhC) cavity, where the heat flux produced by the PhC cavity can be efficiently dissipate along the in-plane direction of the SLG. The thermal properties of the graphene-capped PhC cavity were characterized by experiments and theoretical calculations. The simulation showed that SLG received the majority of the heat fluxes during the dissipative process, which resulted in a substantially lower temperature in the SLG-capped PhC cavity compared with that in the bare PhC cavity. The thermal resistance of the SLG-capped PhC cavity obtained from experiments is lower than half of that for a bare PhC cavity. The temperature of a SLG-capped PhC cavity is 45 K lower than that without SLG capping under an optical power of 100 μW. Both the experimental and simulation results indicate that the SLG is a promising material for the heat dissipation in the compact optoelectronic devices.

9168-31, Session PWed

Mechanical properties and applications of nano carbon-based materials

Shervin Zoghi, California State Univ., Fresno (United States); Davood Askari, Wichita State Univ. (United States); Maziar Ghazinejad, California State Univ., Fresno (United States)

No Abstract Available

9168-11, Session 3

Large-scale characterization of graphene and 2D materials *(Invited Paper)*

Maziar Ghazinejad, California State Univ., Fresno (United States)

I will discuss the current state of large-scale metrology techniques for industrial characterization of 2D materials such as graphene and MoS2. A variety of high-throughput methods for metrology of 2D materials that characterize target properties against desired metrics will be reviewed. Next, I describe how fluorescence quenching metrology (FQM) provides a scalable characterization technique to visually evaluate the quality and identify complex patterns of 2D materials sheets. The method relies on how different 2D materials will photophysically respond when they are coated with proper fluorescence dye. Steady-state and time-resolved absorption and emission spectroscopy are used to characterize the photophysical behavior of 2D materials. It is demonstrated that with an appropriate choice of Fluorophores the interaction between fluorescence dyes and 2D materials can be used for identifying the chemical structure and quality of 2D materials such as graphene. The results show that an industrial characterization technique can be developed based on the fluorescence quenching phenomenon.

9168-12, Session 3

Ultrafast carrier dynamics in graphene quantum dots

Hyojung Kim, Jihee Kim, Sungkyunkwan Univ. (Korea, Republic of); Junichiro Kono, Pulickel M. Ajayan, Rice Univ. (United States); Mun Seok Jeong, Sungkyunkwan Univ. (Korea, Republic of)

Energy bandgap engineering of graphene is one of the main topics in the research community, and thus the size of graphene has been controlled to smaller and smaller, resulting in the bandgap opening. Recently, graphene quantum dots (GQDs) have been fabricated with the size smaller than 4 nm using acidic exfoliation and etching of pitch carbon fibers, leading to strong quantum confinement. For further optical and optoelectrical applications, it is essential to investigate the dynamics of photoexcited carriers in GQDs. Here, we firstly report the carrier dynamics in GQDs using femtosecond transient absorption (TA) spectroscopy to understand the photoexcited carrier distribution, and inhomogeneously broadened absorption spectra on GQDs.

We performed TA spectroscopy with excitation wavelengths at resonance (520 nm, 2.38 eV), and above resonance (350 nm, 3.54 eV), respectively. TA signal was probed by white light continuum (WLC), ranging from 450 to 750 nm (2.75 eV~1.65 eV). To generate WLC, an amplified Ti:sapphire laser with 1-kHz repetition rate and 800 nm (1.55 eV) center wavelength was focused on the CaF2 crystal.

The power-dependent TA signal in GQDs is measured with the pump pulse at 350nm (3.54eV), which is above resonant energy. We could observe snapshots of photoexcited carrier distribution in GQDs from different time delays. The carriers decay rapidly when the excitation power is higher due to strong Coulomb interaction. Furthermore, we observed the dynamic spectral hole-burning effects in GQDs at resonant energy, 520 nm (2.38 eV). We will analyze and discuss these ultrafast carrier dynamics results in GQDs.

9168-14, Session 3

Semiconducting 2D TMDCs: synthesis and characterization

Zafer Mutlu, Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

Layered transition metal dichalcogenide semiconductors such as WS2 and MoS2, with an indirect band gap in bulk form and a direct band gap in monolayer layer form, exhibits tunable electronic properties, allowing realization of advanced optoelectronic devices, transistors, valley polarization devices and spintronic components. To enable practical applications of large-area, high quality 2D materials at the centimeter and wafer scales, process control needs to be implemented for optimizing the morphology and electrical properties of grown layers. Herein, we have successfully synthesized large-scale single-and few-layered MoS2 and WS2 sheets by chemical vapor deposition technique. Raman-PL spectroscopy and ab-initio density-functional-theory computations are used to evaluate the optical properties and electronic band structures of grown layers. Surface morphology, thickness and quality of the layers are studied by SEM, AFM and OM. Furthermore, we have studied the electrical transport properties of the synthesized layers using back- and top-gated FETs.

9168-15, Session 3

Simulation of Maxwell-Dirac equations in graphene nanostructures

Xuecang Zhang, Huawei Technologies Co., Ltd.. (China)

Graphene, with many supreme properties such as the extremely high carrier mobility, is a highly attractive and promising material for numerous applications, particularly in high performance electronic and photonic devices. Simulation of the coupling transport of electromagnetic fields and carriers in graphene nanostructures is of great importance for the analysis and design of graphene optoelectronic nanodevices. According to the rigorous quantum electrodynamics, the most fundamental model for this coupling transport is the Maxwell-Dirac equations. In this paper, for the first time, we derive the appropriate form of Maxwell-Dirac equations for graphene nanostructures, and propose a time splitting spectral method for the numerical solution of this multiphysics problem.

In this time splitting spectral method, we split each time step into three substeps. In each substep, we split the linear and nonlinear parts of the complicated nonlinear coupling Maxwell-Dirac system, then iteratively solving each simple part by linearizing the nonlinear part. The time derivatives are discretized by finite difference method with second order accuracy schemes. The spatial differential operators are approximated by spectral differentiation matrices. The proposed numerical method is validated by numerical examples that simulate the propagation of electromagnetic wave in graphene nanowaveguides.

9168-16, Session 3

Electron dynamics in graphite studied by femtosecond two-color pump-probe spectroscopy

Seungwon Seo, Chungnam National Univ. (Korea, Republic of); Ho Jong Kim, Su Yong Jeong, Korea Research Institute of Standards and Science (Korea, Republic of); Kwang-Jun Ahn, Seoul National Univ. (Korea, Republic of); Ki-Ju Yee, Chungnam National Univ. (Korea, Republic of)

We measured time-resolved reflectance change in graphite by two-color pump-probe spectroscopy. Graphite samples were made by the scotch tape method on a Quartz substrate with 25 nm Titanium and 300 nm SiO2 layer. The pump beam was from an optical parametric oscillator(OPO) laser. The wavelength of the OPO laser was variable, we used 1200 nm ~ 2500 nm from the signal and idler part. The probe beam was obtained from supercontinuum source that had broad wavelength, we selected 500 nm ~ 1200 nm. The experiment results show that there are two characteristic times in the decay of the reflectance. After the electrons were excited, the electron temperature is very high, as time goes on, the temperature is decreased towards the lattice temperature through the intra band relaxation process. So, the faster decay factor is related with the change of the temperature because of the Fermi-Dirac distribution. The other slower decay factor is related with the change of refractive index through the carrier recombinations. Although the recombining carriers may have lower energies than the probe photons, this process can affect the probe reflectance because of the Kramers-Kronig relation. From the change of the reflectance, absorption change can be calculated in graphite for each probe wavelength. Then, the electron temperature and chemical potential are determined by the absorption change. Finally, we map the electron distribution as a function of time delay from the obtained electron temperature and chemical potential until the excited electrons return to the initial stage.

9168-30, Session 3

Titanium carbide coated graphite: a unique material combination

Vilupanur A. Ravi, Mehrdad Haghi, California State Polytechnic Univ., Pomona (United States)

Titanium carbide-coated graphite is a novel material that combines the hardness of a ceramic with that of a soft and easily machinable substrate. There are several other advantages to this coating/substrate combination, e.g., graphite is lightweight and has excellent chemical stability while titanium carbide is also quite stable in a broad range of corrosive media while also being wear resistant. One of the unique features of this material is the specular reflection from the as-coated surface that is akin to the reflection from a polished metallic surface. There are some issues with microcracking of the coatings due to the thermal coefficient of expansion mismatch between the carbide and the graphite substrate. In this presentation, we will discuss different aspects of this material including the coating microstructure, non-stoichiometry of the coating and consequences, thermomechanical modeling, corrosion and wear/erosion behavior of the coatings. Some potential applications will be discussed as well.

9168-17, Session 4

Graphene materials for advanced energy storage *(Invited Paper)*

Cengiz S. Ozkan, Univ. of California, Riverside (United States)

Graphene is a one atom thick two-dimensional material that exhibits exceptional physical and electronic properties, and offers alternatives for applications in energy storage devices, nanoelectronics, spintronics, biosensors, and medicine. I will describe innovative approaches for the synthesis of hierarchical three dimensional graphene hybrid materials which possess characteristics including ultra large surface area, mechanical durability and high conductivity which are appealing to diverse energy storage systems. Rapid charging and discharging supercapacitors are promising alternative energy storage systems for applications such as portable electronics and electric vehicles. Integration of pseudocapacitive metal oxides with structured nanomaterials has received a lot of attention recently due to their superior electrochemical performance. In order to realize high energy density supercapacitors, we developed a simple and scalable method to fabricate graphene/MWNT/MnO2 nanowire hybrid systems. Excellent capacitance retention and high charge-discharge cycles have been demonstrated. Next, I will talk about three-dimensional cone-shape carbon nanotube clusters decorated with amorphous silicon for lithium ion battery anodes. The seamless connection between silicon decorated CNT cones and graphene facilitates the charge transfer in the system and provides a binder-free technique for fabricating lithium ion batteries. Very high reversible capacity and excellent cycling stability has been demonstrated. Such multi-scale engineered materials could have wide range implications to facilitate new technological innovations in energy storage.

9168-18, Session 4

Thermoelectric, electro-thermal, and opto-thermal characterization of thin film CNT devices consisting of dense, aligned, and macroscopically long SWCNTs

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Understanding the thermoelectric, electro-thermal and opto-thermal properties of CNT devices is critical for their application as sensors, photo-detectors, power generators and for thermal management. We investigate these properties in devices consisting of dense, aligned, and macroscopically long SWCNTs, including those with p-n junctions. Results from Joule heating, focused laser illumination, direct heating, and electronic transport experiments, with accompanying models, are presented for the thorough analysis of device thermoelectric, electro-thermal and opto-thermal properties. As example applications, we determine the ZT factor of CNT devices, and demonstrate the photothermoelectric origin of photocurrent in novel CNT IR and THz detectors.

9168-19, Session 4

Intrinsic regime of exciton photophysics in ultra-clean carbon nanotubes bridging an air gap

Ibrahim Sarpkaya, Stevens Institute of Technology (United States); Zhengyi Zhang, Columbia Univ. (United States); William Walden-Newman, Stevens Institute of Technology (United States); James Hone, Chee Wei Wong, Columbia Univ. (United States); Stefan Strauf, Stevens Institute of Technology (United States)

Carbon nanotubes (CNTs) have recently gained tremendous interest as a nanomaterial for next generation optoelectronics and quantum photonic devices.

However, to date, the photophysics of excitons in carbon nanotubes is largely affected by extrinsic effects. This is very detrimental for optoelectronic device applications since low quantum efficiencies due to dominant non-radiative optical recombination processes leads to strongly reduced optical emission rates of nanoscale light sources as compared to, e.g., semiconductor quantum dots. To overcome these extrinsic effects we have combined sophisticated growth of ultra-clean SWCNTs bridging an air gap over pillar posts with time-resolved photoluminescence measurements of individual SWCNTs over 14 orders of magnitude. Our measurements demonstrate a new regime of intrinsic exciton photophysics with narrow spectral linewidth down to 200 μeV and prolonged spontaneous emission times up to T1=18 ns, about two orders of magnitude better than prior measurements and in agreement with values(10-100ns) hypothesized by theorists about a decade ago.

With these supposedly ultraclean air-bridged samples we also carried out first experiments on exciton dephasing times for individual SWCNTs in the time-domain. The interferometric measurements demonstrated exciton dephasing times up to 2 ps, about four-fold longer than in previous ensemble studies (500 fs).

The ultra-narrow linewidth and prolonged exciton dephasing times suggest that the acoustic phonon coupling giving rise to exciton dephasing is significantly weaker than previously believed, which is promising news for device applications, and raises the question about the ultimate limit for SE lifetimes and exciton dephasing in the intrinsic regime.

9168-20, Session 4

Pillared graphene nanostructure for ultrafast charge and discharge energy storage devices

Wei Wang, Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

In this work, we report on an innovative of pillared graphene nanostructures (PGN) directly on conductive substrates by an ambient

pressure chemical vapor deposition (APCVD) process. The seamless connection between current collector and activae materials provides a relatively strong electrode integrity, which facilitates charge transfer in the system. Symmetrical supercapacitors (SCs) are fabricated based on this hybrid CNT and graphene nanostructure. SCs based on PGN show superior high-rate handability of up to 100 V sec-1. The electrochemical stability, excellent capacitive performance, and the ease of preparation suggest this PGN system is promising for future energy storage applications.

9168-33, Session 4

Cu surface morphology affects on self-limiting single layer growth of graphene films by chemical vapor deposition

Isaac Ruiz, Zafer Mutlu, Robert Ionescu, Mihrimah Ozkan, Lauro Zavala, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

The synthesis of graphene with large-area uniformity is an essential requirement for their application in electronic and optical devices. Here, we reported on fast synthesis of large-scale single layer graphene with no annealing and growth times of less than 1 minute by oversaturating Cu foils with a high precursor partial pressure via chemical vapor deposition (CVD). To understand the growth mechanisms involved, the effect of Cu foil properties (purity, manufacturer and surface morphology) and growth parameters (growth time, pressure, annealing pre-treatment time and precursor partial pressure) on fast synthesis of graphene films was systematically investigated using Raman spectroscopy, atomic force microcopy, scanning electron microcopy and optical microcopy. We showed that certain foils promote self-limited growth of graphene films without any pre-treatment, while other foils favor the growth of thick graphitic like films or single- and multi-layered graphene films by depending on the type and surface morphology of Cu foils. Furthermore, we examined changes in the surface morphology of Cu foils using electropolishing. Microscopic observations revealed that surface polishing of inexpensive low purity Cu foil, which previously yielded a thick graphitic film, could promote the single layer growth of graphene with large-area uniformity.

9168-21, Session 5

Cross-linked carbon nanotube thick films

Gregory A. Konesky, K-Plasma Ltd. (United States)

The use of heat spreaders allows the thermal footprint of a semiconductor device to be expanded, permitting laser diodes to operate at higher powers or computer processing chips to operate at higher clock speeds. The heat spreader must necessarily have high thermal conductivity and be thermally isotropic. Heat spreaders have been constructed of a copper and diamond powder composite and provide a thermal conductivity typically between 600 and 800 W/m K at moderate cost. CVD diamond heat spreaders can provide thermal conductivities of 1000 W/m K but have relatively high cost. We have experimented with the use of argon ion bombardment to join adjacent and overlapping CNTs in a thick film to form a continuously interconnected network whose thermal conductivity is isotropic. A 1 cm2 film of multi-wall CNT (MWCNT), 5 µm thick was subjected to a 4 keV argon ion bombardment with a total fluence of approximately 2.25 x 10^17 ions. A change in morphology was observed, from unprocessed MWCNT films that rather resemble a “bowl of spaghetti,” to individual nanotubes being joined at points of intersection. Thermal conductivity was measured using the 3? technique and indicated an isotropic thermal conductivity of 2150 W/m K. Upon closer examination under high magnification (800,000X), it becomes clear that overlapping MWCNTs were not just attached by their outer walls, but became fully interpenetrating. A mechanism is explored whereby overlapping MWCNTs, when struck by an argon ion of sufficient energy, have that area briefly disrupted, and then self-reassemble into an interpenetrating junction.

9168-22, Session 5

Nanoporous graphene sponge for supercapacitor electrodes

Hamed Hosseini Bay, Daisy Patino, Zafer Mutlu, Paige Romero, Mihrimah Ozkan, Cengiz S. Ozkan, Univ. of California, Riverside (United States)

Graphene is a unique two dimensional material with exceptional physical and chemical properties. The theoretical surface area of graphene is reported to be 2630 m2g-1, which is significantly higher than activated carbons, graphite and single-walled carbon nanotubes. As a result, graphene and graphene based composite materials have been of great interest for various applications in energy storage/production. Accordingly, owing to its high surface area, graphene is a decent candidate as an electrode in electrochemical supercapacitors. Recent studies indicate that graphene demonstrates the highest capacitance among all carbon-based electrodes for supercapacitors. Moreover the graphene sheets surface is readily accessible by electrolyte. Herein, to increase the capacitance of graphene as well as the power and energy density, a novel porous 3-dimensional graphene-based structure is synthesized by a modified CVD method. In this case, no chemical treatment or activation is necessary and the process is not subjective to particular catalyst substrates. To prepare precursor materials for such structure, a modified sol-gel process has been implemented. Nanostructure samples were characterized by Raman Spectroscopy, Optical Microscopy, Scanning Electron Microscopy, Transmission Electron Microscopy and BET technique. Cyclic voltammetry measurements were also carried out and the results suggest that the use of 3-dimensional nanoporous graphene sponge as electrodes for supercapacitors can be a potential way to achieve enhanced gravimetric capacitance as well as higher energy and power density.

9168-23, Session 5

Enhanced D- and G-band signals from silver-dressed carbon nanotubes

Paul Dawson, Queen’s Univ. Belfast (United Kingdom); Jose A. Duenas, Univ. de Huelva (Spain); William I. Milne, Univ. of Cambridge (United Kingdom); Olivier J. F. Martin, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Carbon nanotubes have been used as a micro- to nano-scale scaffolding for forming general SERS substrates[1,2] where the key functionalization step has been the deposition of a (highly granular) noble metal film, sometimes directly on the CNTs[1] and sometimes with an intermediate dielectric spacer[2]. Here, however, we focus on the enhanced Raman signal from the CNTs themselves where the D- and G-band signals from a forest of vertically-aligned, multi-walled CNTs are enhanced by a factor of 10-20 when dressed (capped or coated) with silver. These plasmonic structures – supporting highly localised plasmons (silver-capped case) and/or more extended optical antenna-like modes (silver-coated case) – offer a novel and unusual instance of SERS in that the enhancement interaction takes place at the inner interface of the silver dressing. Nonetheless, the enhancement is greater than that reported for nanotubes deposited on rough silver or gold substrates. Moreover, spatially resolved mapping of the D- and G- band intensities reveals good uniformity of the signal enhancement, with very few hot- or dead- spots on the ~micron scale of the focused input beam. The Ag-dressing procedure thus offers a reliable Raman-scattering based means of characterizing CNTs, but with significantly increased sensitivity, extendable to the probing of individual CNTs. The results are analysed with reference to experimental comparator cases and to modelling of the electromagnetic response of the system.

[1] P. Dawson et al., Nano Lett. 11, 365-371 (2011)

[2] A.O. Altun et al. Adv. Mater. 25, 4431 (2013)

9168-24, Session 5

Nano porous graphene room temperature field effect transistor fabricated using self-assembled mask technique

Duyoung Choi, Cihan Kurua, Sungho Jin, Univ. of California, San Diego (United States)

We have successfully fabricated and characterized nano-porous graphene (NPG) with neck width of sub-20 nm. Anodized aluminum oxide nano-mask was prepared by facile and simple self-assembly technique without using polymer buffer layer, which was utilized as a template for oxygen plasma etch to produce near periodic NPG. The NPG exhibits a homogeneous mesh structure with an average neck width of 10 nm ~ 19 nm. The sub-20 nm neck width creates a quantum confinement in NPG, which has led to a bandgap opening of ~ 0.2 eV in graphene. Electronic characterization of single layer NPG field effect transistors (FETs) were performed at room temperature. We found that the NPG allows for experimental confirmation of the relationship between electrical conductance and bandgap. Electrical characterization of NPG confirmed that the current on-off ratio is inversely proportional with neck width, indicating the formation of an effective gap due to the confinement effect. The electrical resistance of the graphene increases significantly by a factor of ~x15 by removal of substantial graphene regions via nano-patterning into hexagonal array pores. It is likely that the availability of large number of edges created in the NPG provides ideal sites for chemical attachment, leading to a significant reduction of the RS. We have shown that both electronic transport and Raman characteristics change in a concerted manner on graphene patterning. The availability of such NPG will provide an interesting system for fundamental investigation of transport behavior in the highly interconnected graphene network, and will enable exciting opportunities in sensitive biosensors and a new generation of devices.

9168-29, Session 5

A comparative study of thermal interface materials with graphene, carbon nanotube, and boron nitride fillers

Fariborz Kargar, Univ. of California, Riverside (United States); S. Legedza, Quantum Seed LLC (United States); R. Salgado, P. Goli, Univ. of California, Riverside (United States); J. Renteria, Quantum Seed LLC (United States); Alexander A. Balandin, Univ. of California, Riverside (United States) and Quantum Seed LLC (United States)

Rapidly increasing power densities in electronics make efficient heat removal a crucial issue. Development of the next generations of integrated circuits requires substantially improved thermal management. Thermal interface materials (TIMs), applied between heat sources and heat sinks, are essential ingredients of thermal management. Conventional TIMs filled with thermally conductive filler materials require high volume fractions of filler (f~50%) to achieve thermal conductivity of the composite in the range of ~0.5-5 W/mK at room temperature. The discovery of unique heat conduction properties of graphene [1-2] stimulated research work directed at the use of inexpensive liquid phase exfoliated graphene as fillers for TIMs [3-4]. The present study addresses an important question of comparing graphene performance as filler materials with that of carbon nanotubes (CNTs) and boron nitride (BN) flakes. The measurements have been conducted using the standard TIM tester. Our results show that adding a small fraction of graphene (f=4%) to a commercial TIM increases the resulting thermal conductivity much stronger than the addition of CNTs or BN. The obtained data suggest that graphene and few-layer graphene couple better to the matrix materials than the alternative fillers. [1] A.A. Balandin, et al., Nano Lett., 8, 902 (2008); [2] A.A. Balandin, Nature Mat., 10, 569 (2011); [3] K.M.F. Shahil and A.A. Balandin, Nano Lett., 12, 861 (2012); [4] V. Goyal and A.A. Balandin, Appl. Phys. Lett., 100, 073113 (2012).

9169-1, Session 1

Sub-Abbe resolution in STED lithography and bio-applications *(Invited Paper)*

Thomas A. Klar, Johannes Kepler Univ. Linz (Austria)

Similar to the further development of two-photon microscopy into two-photon lithography[1], it was proposed already in the early reports of STED microscopy that the confined excitation volume can be applied to spatially control chemical reactions on the nanometer scale[2].

In this contribution, we address the question of minimal structure size and minimal resolution in STED-lithography. We show that free standing lines can be written with a lateral[3] and axial width of only 55 nm. The structures show good biocompatibility and allow for bio-functionalization with proteins, down to the single protein level[4]. The ability to place individual proteins into nano-confined spaces plays a growing role in bioscience, from basic studies in biology to the development of nanoscopic sensors.

While STED-lithography cannot (yet) compete with UV or with electron beam lithography, there is justified hope that both, feature size and resolution can further be improved within the next years, similar to STED nanoscopy which started with a resolution above 100 nm and has reached sub-10 nm resolution meanwhile. Compared to UV and e-beam lithography, STED-lithography has two major advantages. First, it is capable of three dimensional structuring. Second, photons of visible light contain much less energy compared to UV photons or accelerated electrons and hence, photosensitive substrates such as polymers or even living tissue might be structured.

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[4] Wiesbauer et al., Nano Lett. 13, 5672 (2013).

9169-2, Session 1

Nanoparticle-assisted STED, theory, and experimental demonstration *(Invited Paper)*

Yannick Sonnefraud, Institut NÉEL (France); Yonatan Sivan, Ben-Gurion Univ. of the Negev (Israel); Hugo G. Sinclair, Christopher W. Dunsby, Mark A. Neil, Paul M W. French, Stefan A. Maier, Imperial College London (United Kingdom)

We show that metal nanoparticles can be used to improve the performance of super-resolution fluorescence nanoscopes based on stimulated-emission-depletion (STED). Compared with a standard STED nanoscope, we show theoretically a resolution improvement by more than an order of magnitude, or equivalently, depletion intensity reductions by more than 2 orders of magnitude and an even stronger photostabilization.

Moreover, to demonstrate the effect, we compare the resolution attained imaging dye-doped silica nanoparticles with or without a shell of gold. To do so, at first confocal images of single NPs of the two sets are recorded, followed immediately by a STED image. The same process is repeated for varying STED beam power. The resolutions obtained in both images are compared and an improvement using STED calculated. We observe that an optimum resolution, limited by the particle sizes, can be reached for the hybrid NPs for a power of the STED beam one order of magnitude smaller than for the bare cores.

This demonstration opens the door to improvement of existing STED nanoscopes by assisting in the development of low-power, low-cost nanoscopes. This has the potential to increase the availability of STED nanoscopes and lead to a significant expansion of our understanding of biological and biochemical phenomena occurring on the nanoscale.

9169-3, Session 1

Breaking diffraction limit: integrated hybird-superlens hyperlens for diffraction limit *(Invited Paper)*

Din Ping Tsai, Academia Sinica (Taiwan)

We numerically propose an innovative device for magnifying far-field image by finite element method (FEM) simulation. It possesses ability to image a sub-wavelength object at far field and compensate the drawbacks of the proposed hyperlens so far. This device is integrated with two kinds of anisotropic metamaterial, including the upper planar superlens and the lower cylindrical hyperlens, in which the signs of permittivity tensors are opposite. Since the specific dispersion relations between these two components, such proposed device is named as the "Hybrid-Superlens Hyperlens", which is capable of deriving the high spatial-frequency components excited by the objects on one flat surface and transferring it to far field.

Basically, the polarization of light source is an important factor for plasmon based imaging devices because it may affect the integrity of resolution image which is resulting from the excited surface plasmon polarions (SPPs) near the patterned region. Therefore, we also theoretically investigated the imaging characteristics of hybrid-super-hyperlens with both linearly and radially polarized illumination. We further demonstrate that the whole magnifying far field images can be obtained at one scan procedure by using radially polarized light source, that is, superposition of the images under incident light with different polarized directions is unnecessary. This planar shape design has great potential for practical applications such as photolithography and planar integrated optical devices.

9169-4, Session 1

Conical diffraction as a versatile building block to implement new imaging modalities for superresolution in fluorescence microscopy

Clément Fallet, Julien Caron, Stephane Oddos, Bioaxial (France); Jean-Yves Tinevez, Institut Pasteur (France); Lionel Moisan, René Descartes Univ. (France); Gabriel Y. Sirat, Philippe O. Braitbart, Bioaxial (France); Spencer L. Shorte, Institut Pasteur (France)

We present a new technology for super-resolution fluorescence imaging, based on conical diffraction. Conical diffraction is a linear, singular phenomenon taking place when a polarized laser beam is diffracted through a biaxial crystal. The illumination patterns generated by conical diffraction in thin biaxial crystal that are sharper than the classical Gaussian beam, and we use them to generate a super-resolution imaging modality.

Whereas most of the current technologies in superresolution use non-linear processes and require high quality immersion objectives and dedicated sample preparation, Bioaxial SuperResolution (BSR) resolution enhancement can be achieved with any type of objective no matter the magnification, numerical aperture, working distance, or the absence or presence of immersion medium on any kind of sample preparation and standard fluorophores.

The system generates datasets made of thousands of images, one for each beam shape and beam position, similarly to some other Image Scanning techniques. Given the low light doses used in each image, the data formation derives from a linear model with limits predicted by Fourier analysis and recent superresolution theory developments. In the framework of Bayesian Inverse Methods, we developed two numerical solvers which exploit the data formation model and the noise distribution in modern low-light cameras.

This technique has been successfully used for live-cell super-resolution imaging over a long period, and shows that the light dose required for super-resolution imaging is far below the threshold likely to impact phototoxicity.

9169-5, Session 2

Correlation studies between localized surface plasmons and surface-enhanced Raman scattering of Gold-Silver NanoDumbbells (GSNDs) at the single-particle and single-molecule level *(Invited Paper)*

Haemi Lee, Korea Research Institute of Chemical Technology (Korea, Republic of); Yung Doug Suh, Korea Research Institute of Chemical Technology (Korea, Republic of) and Sungkyunkwan Univ. (Korea, Republic of)

Fabricated plasmonic nanostructures (especially structures with plasmonic nanogap) have been of major interest to scientific and engineering communities because of their interesting and useful optical properties. However, the exact relationships between their structure and various optical properties such as surface-enhanced Raman scattering (SERS) and localized surface plasmon (LSP) are not clearly known yet, and it still requires deeper understanding of their relationships between structure and optical properties for the reliable utilization of these structures in various applications. In particular, SERS originates from a highly localized region referred to as hot spot in a plasmonic gap typically with less than a few nanometers whereas Rayleigh scattering originates from the induced dipole moment occurred near a nanostructure. Such distinct physical origins thus invoke the intrinsic limitation in correlation of those optical signals.

In this talk, we present that there is a strong positive relationship between the coupled dipolar/quadrupolar LSPs and SERS intensity of dimeric Au-Ag core-shell nanodumbbell (GSND) structures with ~0.9-nm nanogap, using a multistep tip-matching-based high-precision correlation measurement. Our result can be particularly useful in probing the complicated interactions among the different modes of LSPs, thereby elucidating the relationship between the SERS activity and LSPs in which complex interactions of each LSP mode are involved (H. Lee et al. Nano Lett. 2013, 13, 6113). This observation thus suggests that our correlation approach using Rayleigh scattering and SERS is useful and could overcome the intrinsic limitation in correlating Rayleigh scattering with SERS caused by the difference in the far-field and near-field characteristics of Rayleigh scattering and SERS, respectively. Also, we present there is a specific interaction between longitudinal quadrupolar and transverse dipolar LSPs from a minor population of dimers and show that this interaction results in a strong SERS signal.

9169-6, Session 2

3D plasmonic nano imaging and spectroscopy of a living cell with a gold nanoparticle *(Invited Paper)*

Satoshi Kawata, Katsumasa Fujita, Nicholas I. Smith, Osaka Univ. (Japan); Jun Ando, RIKEN (Japan); Kazuki Bando, Osaka Univ. (Japan); Kai-Chih Huang, National Taiwan Univ. (Taiwan)

Raman scattering microscopy visualizes molecular distribution in a sample without any labeling or modification [1]. Tip-enhanced Raman scattering (TERS) microscope has been successfully used for visualizing molecular distribution at nanometer resolution, while its application is limited to surface imaging [2]. We have developed a SERS microscope with a gold nanoparticle as a probe, which is captured in a biological cell and works as a nano-light source [3]. The nanoparticle travels inside the cell, meeting local molecules. Raman signal scattered at a local molecule along the path is enhanced by the nanoparticle. As a result, molecular distribution along the cellular pathway is collected. The nanoparticle position in during motion was precisely tracked with high-resolution CCD in three dimensions through a dual-focus dark-field microscope, while Raman scattering is detected with spectrophotometer with the feedback system to control the particle image fixed at the slit [4]. We achieved a temporal resolution of 100ms for both particle tracking and Raman spectroscopy. In the presentation, we will show the result of molecular imaging in a living cell in three dimensions, which represents the cellular function of biomolecules associated with organelle transportation and lysosomal accumulation.

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9169-7, Session 2

Residual pesticide detection on food with particle-enhanced Raman scattering

Bikas Ranjan, Huang LiChuan, Kyoko Masui, Yuika Saito, Prabhat Verma, Osaka Univ. (Japan)

Modern agriculture relies highly on pesticides to protect agricultural food items from insects for high yield and better quality. Increasing use of pesticides has raised concern about its harmful effects on human health and hence it has become very important to detect even small amount of pesticide residues. Raman spectroscopy is a suitable nondestructive method for pesticide detection, however, it is not very effective for low concentration of pesticide molecules. Here, we report an approach based on plasmonic enhancement, namely, particle enhanced Raman spectroscopy, which is rapid, nondestructive and sensitive. In this technique, Raman signals are enhanced via the resonant excitation of localized plasmons in metallic nanoparticles. As plasmonic resonance frequency highly depends on the shape, size and material of nanostructures, hence it is possible to grow nanoparticles of a chosen shape and size to tune its plasmonic resonance with the resonance of Raman signals of any desired pesticide for better enhancement. Gold is a promising material that has ability to tune surface plasmon resonance frequency in visible to near-IR, which depends on shape and size of nanostructures. We synthesized desired shape and size of gold nanoparticles by using seed mediated growth method, and successfully detected very tiny amount of two pesticides, named benomyl and polycarbamate. We also confirmed that the detection of these pesticides was not possible by usual Raman spectroscopy.

9169-8, Session 2

Multi-wavelength surface-enhanced Raman scattering metasurface with broadband absorption over large area

Nan Zhang, Kai Liu, Haomin Song, Xie Zeng, Dengxin Ji, Qiaoqiang Gan, Univ. at Buffalo (United States)

Surface-enhanced Raman spectroscopy (SERS) refers to a vibrational spectroscopy technique for the characterization of low concentration analytes bound to or near plasmonic surfaces. It has been widely used as a highly surface-sensitive and label-free analytical technique for chemical and biological sensing applications down to single molecule level. Therefore, substrates with localized enhanced electromagnetic field that can excite strong Raman scattering are heavily required. Current dominant substrate fabrication techniques include electron beam lithography, nanoimprint, self-assembled nanosphere, and hybrid nanoporous lithography, which are time-consuming and costly methods only suitable over small areas. In addition, most SERS substrates were designed for a particular excitation wavelength only, which limited measurements of different molecules excited by the optimal laser lines

with higher SERS signals. To overcome these limitations, we report a simple and cost-effective method to manufacture large-scale three-layered super absorptive SERS metasurfaces using direct sputtering deposition. By controlling the deposition and post thermal treatment conditions, random metallic nanoparticles can be formed simply on a diverse range of substrates to function as the nanoantennas supporting strongly enhanced localized plasmon modes. Due to the randomly distributed dimension of these nanoantennas, broadband plasmonic absorption over 80% ranging from 450 nm to 1000 nm can be obtained, which generates strong enhancement of the excitation and Raman scattered signal simultaneously. Using this substrate, we achieved a high area-average EF of 8.2 x 10^6 and excellent uniformity with only 14.5% variation simultaneously over the entire sample area, which is better than many commercial SERS substrates.

9169-9, Session 3

Superresolution microscopy through thick tissue using adaptive optics *(Invited Paper)*

Brian R. Patton, Robert Vrees, Daniel Burke, Univ. of Oxford (United Kingdom); Travis J. Gould, Joerg Bewersdorf, Yale School of Medicine (United States); Martin J. Booth, Univ. of Oxford (United Kingdom)

Superresolution microscopes have been able to resolve features on the scale of tens of nanometers and lower. These microscopes - including scanning methods (STED, RESOLFT, etc.) and stochastic wide field methods (PALM, STORM, GSDIM, etc.) - all suffer from the effects of aberrations that compromise resolution, signal and consequently image quality. Adaptive optics has been demonstrated in a range of diffraction-limited resolution microscope modalities to compensate for system and specimen-induced aberrations. However, the use of adaptive optics in superresolution microscopes presents new challenges. We investigate how aberrations affect the properties of superresolution microscopes and develop new adaptive optics schemes to measure and correct the aberrations. In particular we show how the commonly-used 2D STED configuration is robust to aberrations, whereas the 3D STED configuration is particularly sensitive. A new scheme is presented that permits the adaptive compensation of aberrations in the 3D STED microscope through optimization of a new application of the Fourier Ring Correlation image quality metric. This system is used to perform three-dimensionally resolved superresolution imaging through thick (~10 to 50 micrometre) specimens. Significant improvements in resolution and image intensity are achieved. The adaptive correction of specimen-induced aberrations in this manner will be an essential step to the wider use of superresolution methods in a wider range of biologically relevant specimens.

9169-10, Session 3

Adaptive optics STED microscopy in thick biological tissue *(Invited Paper)*

Mary Grace M. Velasco, Travis J. Gould, Edward Allgeyer, Emil Kromann, Yale Univ. (United States); Daniel Burke, Martin J. Booth, Univ. of Oxford (United Kingdom); Joerg Bewersdorf, Yale Univ. (United States)

Super-resolution microscopy techniques have realized sub-diffraction limit resolution on the order of tens of nanometers. For thick samples such as tissue sections, stimulated emission depletion (STED) microscopy is the preferred super-resolution method due to its basis on a confocal laser scanning geometry that provides optical sectioning. To achieve super-resolution, STED microscopy incorporates a high-intensity “donut-shaped” laser focus into a conventional confocal setup. If this focus is super-imposed onto the diffraction-limited focus of the excitation laser, fluorophores at the periphery of the excitation focus will be quenched via STED while those in the center can still fluoresce. In this way, the effective point-spread function is engineered to a sub-diffraction size.

The quality of the donut is critical to achieving super-resolution via STED. If the intensity in the donut center is non-negligible, fluorescence will be suppressed in that region as well, thus negating any resolution enhancement. This is of particular concern when attempting 3D STED in thick tissue sections since sample-induced aberrations compromise the quality of the donut shape and impose a practical limit on the maximum depth to which one can image. To overcome this constraint, we employ adaptive optics to correct specimen-induced aberrations. Using spatial light modulators and a novel image quality feedback metric, we demonstrate on-the-fly correction of the random aberrations introduced by a thick tissue sample. This implementation of adaptive optics can be modified for use in in vivo neuroimaging via STED, which has to date been limited to the superficial layers of the mouse cortex.

9169-11, Session 3

Size matters: STED imaging of functional neuroanatomy *(Invited Paper)*

Valentin Nägerl, Univ. Bordeaux Segalen (France) and CNRS (France)

Neurons span an incredibly complex and beautiful morphology, which is absolutely critical for their function and plasticity. Many key neuronal structures like dendritic spines, axons and glial processes are way too small to be properly resolved by conventional light microscopy, making it difficult to study how the functioning of synapses, neurons and circuits is influenced by dynamic nanoscale anatomical structures.

I will review our progress in developing STED microscopy, which provides optical resolution beyond the diffraction barrier, for nanoscale imaging in living brain slices and in vivo, and present several applications regarding synapse biology: 1) nanoscale imaging up to 100 µm below tissue surface in acute brain slices by a combination of two-photon excitation and STED microscopy; 2) regulation of synapse compartmentalization by spine neck plasticity based on a combination of STED imaging, FRAP, patch-clamp electrophysiology and 2P glutamate uncaging experiments; and 3) nanoscale morpho-functional plasticity of axons during LTP by time lapse STED imaging, electrophysiological recordings and computational modeling.

9169-12, Session 3

Three-dimensional optical nanoscopy with opposing lenses

Alexander Egner, Laser-Lab. Göttingen e.V. (Germany)

Far field optical microscopy is a well established method for the non-invasive 3D-investigation of cellular structures. However, the resolution of conventional light microscopy is limited by diffraction to ~200nm in the focal plane and ~600nm along the optic axis. In order to discern identical labels which are much closer than this, one has to overcome the diffraction barrier. The utilization of optical switching events allows one to circumvent Abbe’s diffraction limit: The switching of only markers within an area which is much smaller than the size of a diffraction limited spot to a visible “bright” state while all other markers are switched to a non-visible “dark” state defines a sub-diffraction area. By sequentially recording all areas within the diffraction spot, it is possible to assemble a sub-diffraction image. The first radical concept for improving the resolution of a far field microscope was Stimulated Emission Depletion (STED) microscopy. In this concept the saturated depletion of the excited state of the fluorescent molecule is used to generate a fluorescent spot that is narrower than the diffraction limit. isoSTED microscopy proved a resolution of up to 21 nm in the lateral and 30 nm in the axial direction, meaning that the resolution is higher by more than an order of magnitude as compared to confocal microscopy.

9169-13, Session 3

Using optical lattice for STED parallelization

Bin Yang, Institut d'Optique Graduate School (France); Frédéric Przybilla, Michael Mestre, LP2N,Institut d'Optique d'Aquitaine (France); Jean-Baptiste Trebbia, Brahim Lounis, Institut d'Optique Graduate School (France)

Recent developments in stimulated emission depletion (STED) nanoscopy achieved nanometer scale resolution and showed great potential in live cell imaging. However, STED nanoscopy is a scanning microscope, which constitutes a drawback for fast wide field imaging, since the gain in spatial resolution requires dense pixelation and hence long recording times. Thus STED needs parallelization for fast wide-field imaging. Using well-designed optical lattices for depletion together with wide-field excitation and a fast camera for detection, we achieve large parallelization of STED nanoscopy. Wide field of view super-resolved images are acquired by scanning over a single unit cell of the optical lattice, which can be as small as 290 nm * 290 nm. Optical Lattice STED imaging is demonstrated with a resolution down to 70 nm at 12.5 frames per second.

9169-14, Session 4

Plasmon-assisted chemical reactions revealed by high-vacuum tip-enhanced Raman spectroscopy *(Invited Paper)*

Shuaicheng Lu, Shaanxi Normal University (China); Shaoxiang Sheng, Institute of Physics (China); Zhenglong Zhang, Shaanxi Normal University (China); Hongxing Xu, Institute of Physics (China); Hairong Zheng, Shaanxi Normal University (China)

With strong surface plasmons excited at the metallic tip, tip-enhanced Raman spectroscopy (TERS) has both high spectroscopic sensitivity and high spatial resolution, and is becoming an essential tool for chemical analysis. It is a great challenge to combine TERS with a high vacuum system due to the poor optical collection efficiency. We used our innovatively designed home-built high vacuum TERS (HV-TERS) to investigate the plasmon-driven in-situ chemical reaction of 4-nitrobenzenethiol p-aminothiophenol (PATP) molecules dimerizing to dimercaptoazobenzene, respectively. The chemical reactions can be controlled by the plasmon intensity, which in turn can be controlled by the incident laser intensity, tunneling current and bias voltage. The different substrates of gold and silver films will influence not only the chemical reactions, but also the measured spectroscopic features. The temperature of such a chemical reaction can also be obtained by the clearly observed Stokes and Anti-Stokes HV-TERS peaks. Our findings offer a new way to design a highly efficient HV-TERS system and its applications to chemical catalysis and synthesis of molecules, and significantly extend the studies of chemical reactions.

9169-15, Session 4

Tip-enhanced Raman investigation of "x-shaped" carbon nanotube

Prabhat Verma, Yoshito Okuno, Yuika Saito, Satoshi Kawata, Osaka Univ. (Japan)

The electronic properties of SWNTs can change with deformation, which can be very interesting for devices where one would like to play around with the electronic properties. However, usual Raman microscopy cannot reveal the localization of such changes. In fact, the semiconducting SWNTs can locally show metallic characteristics even with a slight deformation, such as the one caused by the pressure of one SWNT crossing over the other in "X" shape. The effect, however, is extremely localized. We present TERS investigation of extremely localized semiconductor-to-metal transition of SWNTs in such a situation.

9169-16, Session 4

The origin of interferometric effect in scattering near-field scanning optical microscopy

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Scattering near-field scanning optical microscopy (s-NSOM) has been widely used to investigate optical interactions beyond the diffraction limit. With the use of heterodyne or pseudo-heterodyne method, the background noise in s-NSOM can be significantly suppressed, and both amplitude and phase of optical near field can be resolved. Meanwhile, interference patterns are still often observed in s-NSOM measurements. In this work, we investigate the formation of interference patterns appearing in s-NSOM results. We use a single nanoslit to demonstrate the mechanism of formation of these interference patterns: the interaction between the in-plane component of the incident light and SPP launched by the nanoslit. This is in contrast to some other explanations that the SPP is launched from the NSOM probe. In the experiment, we observe a change of periodicity in the interference patterns as the orientation of nanoslit changes. In addition, by changing the laser focusing position relative to the nanoslit, we also observe a variation in the strength of interference, demonstrating SPP launched by the nanoslit is involved in the process. We also use an analytical model and numerical simulations to compute the formation of interference patters. The calculation results reasonably agree with the measurement results, validating the mechanism we proposed. This study will help to understand s-NSOM results from plasmonic nanostructures.

9169-17, Session 4

Aperture-SNOM reveals plasmonic magnetic near-fields

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We report mapping of the lateral magnetic near-field distribution of plasmonic resonant modes in different nanostructure geometries by a hollow-pyramid probe aperture-SNOM. By means of full-field simulations we investigate how the near-field probe acts as a confined local light source and how it efficiently excites surface plasmons. This excitation occurs at lateral magnetic field maxima and affects the detected light intensity, enabling the visualization of the lateral magnetic near-field distribution of surface plasmon modes with subwavelength spatial resolution. Our approach complements the available methods for imaging the different field components of light.

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9169-18, Session 4

Development of a plasmonic tip for the localized studies of magnetic materials

Joshua F. Einsle, Alexander Amy, Queen's Univ. Belfast (United Kingdom); Thomas H. J. Loughran, Euan Hendry, Robert J. Hicken, Univ. of Exeter (United Kingdom); Robert M. Bowman, Paul Dawson, Queen's Univ. Belfast (United Kingdom)

Coupling light into plasmonics excitations on metal dielectric nanostructures has been demonstrated to result in the ability to focus electromagnetic waves for sub-wavelength resolution. (Gramotnev & Bozhevolnyi, 2013) This focusing property has been incorporated into a variety of scanning probe tip systems for improved spatial resolution of nanostructures.(Bao et al., 2012; Johnson et al., 2012; Lindquist, Johnson, Nagpal, Norris, & Oh, 2013; Lindquist, Nagpal, Lesuffleur, Norris, & Oh, 2010; Weber-Bargioni & Schwartzberg, 2011) In all of these systems the response of the sample under study is assumed to have minimal to no impact on the polarization of the electromagnetic wave. Essentially the input and output polarization states are the same. However, for the nanoscale optical study of magnetic systems via the magneto optical Kerr effect, the probing structure needs be able to quantifiably discriminate changes in polarization. Further, in the context of heat-assisted magnetic recording it has been suggested that three-dimensional plasmonic devices offer the ability to both induce both an electromagnetic enhancement as well as sub-wavelength localization in the magnetic material. (Kryder et al., 2008) In this work we will present a variety of gold plasmonics antennas for integration into a Time-Resolved Scanning Kerr Microscope, which address these three key properties (localization, enhancement and polarization discrimination). These devices will allow for the possibility to optically explore the characteristic length scales over which a non-local spin transfer torque may act. This provides an interesting intersection of plasmonics and spintronics.

9169-19, Session 4

Effect of metal tip localized surface-plasmon mode on exciton transport in and radiation emission properties in carbon nanotubes

Andrei Piryatinski, Oleksiy Roslyak, Los Alamos National Lab. (United States); Charles Cherqui, Univ. of Washington (United States); David H. Dunlap, The Univ. of New Mexico (United States)

We report on a general theoretical approach to study exciton transport and emission in a Single-Walled Carbon Nanotube (SWNT) in the presence of a localized Surface-Plasmon (SP) mode within a metal tip interacting via near-field coupling. We derive a set of quantum mechanical equations of motion and approximate rate equations that account for the exciton, SP, and the environment degrees of freedom. The material equations are complemented by an expression for the radiated power that depends on the exciton and SP populations and coherences, allowing for an examination of the angular distribution of the emitted radiation that would be measured in experiment. Numerical simulations for a (6,5) SWNT and cone-shaped Ag metal tip (MT) have been performed using this methodology. Comparison with physical parameters shows that the near-field interaction between the exciton-SP occurs in a weak coupling regime, with the diffusion processes being much faster than the exciton-SP population exchange. In such a case, the effect of the exciton population transfer to the MT with its subsequent dissipation (i.e., the F"{o}rster energy transfer) is to modify the exciton steady state distribution while reducing the equilibration time for excitons to reach a steady sate distribution. We find that the radiation distribution is dominated by SP emission for a SWNT-MT separation of a few tens of nanometers due to the fast SP emission rate, while the exciton-SP coherences can cause its rotation.

9169-20, Session 4

Extending the functions of scanning near-field optical microscopy *(Invited Paper)*

Anke Horneber, Marius F. van den Berg, Jan Rogalski, Eberhard Karls Univ. Tübingen (Germany); Kathrin Swider, Eberhard Karls University (Germany); Kai Braun, Eberhard Karls Univ. Tübingen (Germany); Martin Meixner, Eberhard Karls University (Germany); Alfred J. Meixner, Dai Zhang, Eberhard Karls Univ. Tübingen (Germany)

Scanning near-field optical microscopes (SNOM) are able to correlate local optical properties with topography at the nanometer scale, ideal to investigate material properties. Introducing new microscope functions offer us insights into various aspects, such as morphology related photophysical and photochemical processes.

Using the "lightning rod" and plasmonic effects at an optically excited sharp gold tip apex, our parabolic mirror assisted SNOM has the capability to get below the diffraction limit, improving the optical resolution down to sub-30 nm [1-4]. In order to deal with materials with different optical and conductive properties or surface characteristics, our group further extended the present shear-force feedback based SNOM by introducing three new functions.

• Integrating a scanning tunneling microscope (STM) feedback function: Local structural property related Raman peak shifts and PL intensity variations in graphene will be demonstrated.

• Integrating a photocurrent microscopy function: Raman and photoluminescence spectroscopy combined with local photocurrent detection will be used to investigate the influences of local morphology on the photophysical and photochemical processes in ?-conjugated optoelectronic materials.

• Integrating an ultrafast laser system: Non-linear optical microscopy with signals, such as two-photon-luminescence and second-harmonic-generation, combined with hyperspectral SNOM imaging will be used to study the influences of plasmonic resonances on the non-linear optical properties of metallic nanostructures.

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9169-21, Session 5

Sensitivity, resolution, and speed in detection and tracking of biomolecules *(Invited Paper)*

Jens Ehrig, Marek Piliarik, Susann Spindler, Siegfried Weisenburger, Vahid Sandoghdar, Max-Planck-Institut für die Physik des Lichts (Germany)

Some of the exciting challenges of modern biology and biophysics concern efforts to surpass the limits of conventional optical imaging. In particular, novel contrast mechanisms, sensitivity, signal acquisition rate and spatial resolution have been substantially improved over the past two decades.

In localization microscopy, photobleaching of fluorophores typically limits the localization precision to a few tens of nanometers in state of the art experiments at room temperature. We recently demonstrated Angstrom localization precision by substantially enhancing photostability at cryogenic temperatures [1]. We have now extended this technique to colocalization of two fluorophores on the backbone of a double-stranded DNA. By measuring the separations of fluorophore pairs placed at various design positions, we verify the feasibility of cryogenic distance measurement with sub-nanometer accuracy [2].

The second part of the talk will focus on optical imaging via interferometric scattering detection microscopy (iSCAT) which relies on measuring the interference of the Rayleigh scattering with a reference light beam. Thus, the signal is proportional to the amplitude rather than intensity of the scattered light and allows for the detection of very weak scattering. We demonstrate that using iSCAT it is possible to detect the scattering of individual proteins as small as 60 kDa [3].

Furthermore, using iSCAT we study the diffusion of very small gold nanoparticles (typically 20 nm) attached to GM1 or DOPE lipids in DOPC lipid bilayers at frame rates of up to 1 MHz with nanometer precision [4]. We thus present a very powerful single particle tracking approach that has the potential to resolve some of the longstanding questions of the temporal and spatial scales of heterogeneities in local lipid and protein composition in cell membranes.

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9169-22, Session 5

Nanoscale imaging of neurotoxic proteins *(Invited Paper)*

Clemens Kaminski, Univ. of Cambridge (United Kingdom)

Nanoscale Imaging of Neurotoxic Proteins

Misfolding and aggregation of peptides and proteins is a characteristic of many neurodegenerative disorders, including Parkinson's Disease (PD) and Alzheimer's (AD). Their common feature is that normally unstructured and soluble proteins, misfold and aggregate into insoluble amyloid fibrils, which make up the deposits in the brains of patients suffering from these devastating illnesses. A key requirement to gain insight into molecular mechanisms of disease and to progress in the search for therapeutic intervention is a capability to image the aggregation process and structure of ensuing aggregates in situ.

In this talk I will give an overview of research to gain insight on the aggregation state of alpha synuclein (relevant to PD) beta-amyloid and Tau (relevant to AD) in vitro [1], in cells [2] and in live model organisms [3].

In particular we wish to understand how these and similar proteins nucleate to form toxic structures and to correlate such information with phenotypes of disease [3]. I will show how direct stochastic optical reconstruction microscopy, dSTORM, is capable of tracking amyloidogenesis in vivo and how we can correlate the appearance of certain aggregate species with toxic phenotypes [4].

Using multiparametric imaging methods we follow the trafficking of aggregates between cells and see how the misfolded state propagates from cell to cell. I will show how such information at the molecular level guides our understanding of disease pathology in humans.

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9169-23, Session 5

Optimization of image acquisition parameters for high-speed single molecule switching nanoscopy

Yu Lin, Joerg Bewersdorf, Jane Long, Fang Huang, Whitney Duim, Yale Univ. (United States)

Single Molecule Switching Nanoscopy (SMSN) is a fluorescence microscopy technique that breaks the diffraction limit of resolution at the expense of an increased image recording time. The spatiotemporal resolution of SMSN strongly depends on localization precision, localization density and the photoswitching rate of the fluorophores. Recently, we have reported advances in improving temporal resolution down to 33 ms by combining new sCMOS camera technology, novel sCMOS-specific localization algorithms and high readout laser intensities to induce rapid fluorophore blinking for fast SMSN imaging.

Here we present a study systematically optimizing of excitation laser intensity and camera frame rate to achieve both high precision and high density localizations within a limited time. We performed SMSN on microtubules (MT) of COS7 cells (immuno-labeled for α-tubulin with Alexa 647) at varying laser intensities and frame rates and measured the number of photons detected per switching cycle, the localization uncertainty and density. Our data reveals that laser intensity or exposure time have only a small effect on photon output of Alexa 647. Furthermore, we also demonstrates that imaging at 800-1,600 frames per second (fps) at intensities up to 113 kW/cm2 provides nearly uncompromised localization precision and >3-fold higher localization density in a 10-second interval, than imaging at 50-100 fps at an intensity of 10 kW/cm2 (used traditionally in SMSN).

9169-24, Session 5

High speed fluorescence photoactivation localization microscopy imaging

Andrew J. Nelson, Mudalige S. Gunewardene, Samuel T. Hess, Univ. of Maine (United States)

Fluorescence Photoactivation Localization Microscopy requires the sample of interest to be tagged with a fluorescent label with at least one bright and at least one dark state. Imaging conditions need to be such that most of the label molecules are in the dark state. Typically, the sample is illuminated by two wavelengths of light, an activation wavelength which drives molecules from the dark state to the bright state, and a readout wavelength to excite fluorescence of the molecules in the bright state. At proper intensities, only a subset of the total number of fluorescent molecules will be visible; these molecules are imaged by a camera as a function of time. Eventually, the fluorophores will photobleach, allowing room for new molecules to become activated, fluoresce, and imaged. After many molecules have been imaged, a computer can localize the position of the detected molecules in each frame with uncertainty of a few tens of nanometers. The superresolution image is then constructed from all the localized points. Typically this process can require several seconds to acquire enough data to render an image, which yields a temporal resolution of a few seconds, which is in many cases not suitable for imaging the highly dynamic environment of a living sample. Recently, we have developed methods for imaging fluorescent proteins in living cells with a time resolution of 0.1 seconds, allowing for faster and more representative imaging of living samples. High speed imaging requires high laser intensities and particular attention to limiting sample exposure and optimizing signal to noise. Despite the limitations and challenges of high speed superresolution imaging, these techniques offer researchers the ability to explore an even larger variety of dynamic biological systems.

9169-25, Session 6

Plasmon enhanced spectroscopies *(Invited Paper)*

Peter Nordlander, Rice Univ. (United States)

Metallic nanostructures with their ability of confining and enhancing incident light offer unique possibilities for manipulating light at the nanoscale.[1] Plasmonic nanostructures can also exhibit coherence effects such as Fano resonances where the interference between superradiant and subradiant modes produces extinction features with characteristic narrow and asymmetric line shapes.[2] Due to their narrower spectral width compared to standard plasmon resonances, Fano resonances can provide very large field enhancements.[3] Using symmetry breaking it is possible to tune the Fano interference into specific regimes: a weak coupling regime suitable for LSPR sensing; and a critical coupling regime providing large field enhancements suitable for plasmon enhanced spectroscopies. Finally I will discuss several recent applications where plasmonic Fano resonances have been used to enhance surface enhanced spectroscopies such as SERS[4],four wave mixing,[5] and SECARS.[6]

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9169-26, Session 6

Surface enhancement in UV with variety of nanostructures *(Invited Paper)*

Yuika Saito, Satoshi Kawata, Osaka Univ. (Japan); Atsushi Tagushi, Tokyo Univ. of Agriculture and Technology (Japan); Yasuaki Kumamoto, RIKEN (Japan); Mitsuhiro Honda, Prabhat Verma, Osaka Univ. (Japan)

Localized surface plasmon resonances (LSPRs) have formed the basis of a wide range of nanophotonics research and technologies, including surface-enhanced spectroscopy (SERS) and nano-imaging, ultratrace biochemical sensing, subwavelength optical waveguiding and light manipulation, and light emitters and photovoltaic cells with boosted efficiencies. Although technological developments in these applications have predominantly focused on the visible and near-infrared (NIR) spectral range over the years, there is increasing interest in extending the technology to UV wavelengths. A potential advantage of UV plasmons is the high photon energy that matches the electronic transition energy of many organic molecules and solids. The electronically resonant excitations of materials can be favorably combined with various spectroscopic techniques, such as Raman and fluorescence spectroscopy, which will broaden the scope of the spectroscopic applications of LSPR to include ultra-sensitive detection of DNA and proteins, UV material characterization, and UV nanoimaging.

We performed size-controlled fabrication of Al nanostructure arrays with the aim of providing direct control of the LSPR at UV wavelengths. In order to achieve ultrasmall Al nanostructures, nanosphere lithography (NSL) was used in combination with mask heating to modify the nanosphere mask morphology. By adjusting the fabrication condition, the size of the aperture was continuously reduced until it became infinitesimally small, which realized seamless size reduction of the fabricated aluminum nanostructure.

The fabricated metal nanostructures were actually utilized for surface enhancement in UV range. We will present the application of these nanostructures for SERS and photocatalytic reactions.

9169-27, Session 6

Control over plasmon enhanced Raman and fluorescence from quasi free-standing Au nanorod arrays

Signe Damm, Frances Lordan, Univ. College Dublin (Ireland); Antony P. Murphy, Queen's Univ. Belfast (United Kingdom); Mark McMillen, Queen's University Belfast (United Kingdom); Robert J. Pollard, Queen's Univ. Belfast (United Kingdom); James H. Rice, Univ. College Dublin (Ireland)

Nanoscale structures made from coinage metals such as gold or silver possess localized surface plasmon-polariton (LSP) excitations when the material interacts with light of the correct frequency and polarization. When LSPs are formed strongly enhanced electromagnetic near-fields are generated at the surface of the supporting nanostructure. This property has attracted considerable research interest due to its potential applications in sensors, photonic circuits and medical diagnostics and therapeutics. Metallic nanostructures that possess anisotropic symmetry, such as quasi free-standing Au nanorods and nanotubes, are reported to produce localized surface plasmon-polariton resonances (LSPRs) with high quality factors. LSPs generated from free-standing 2D nanorod and nanotube arrays have been applied to enable surface-enhanced Raman scattering (SERS) and surface enhanced fluorescence (SEF) spectra from Rhodamine 6G molecules adsorbed on the surface of the arrays. Measuring SERS and SEF simultaneously is potentially attractive for sensor applications. But at present, the challenge is to fabricate conditions that enable both SERS and SEF responsive from nanoprobes since the optimum distance between metal surface and probe molecule for enhancing fluorescence emission and Raman scattering is different. Here we study the conditions that optimize SERS and SEF from free-standing Au nanorod and nanotube arrays by studying the effect of changing the surrounding environment using dielectric spacer layers such as Al_2O_3, SiO_2 and solutions. We demonstrate that it is possible to obtain SERS and SEF simultaneously from Au nanorod and nanotube arrays.

9169-28, Session 6

Optical antennas for nanoscale materials characterization *(Invited Paper)*

Joanna Atkin, Univ. of Colorado at Boulder (United States)

Scattering-scanning near field optical microscopy (s-SNOM) consists of focusing light onto a sharp metal tip, which acts as an optical antenna to localize and enhance the optical field. This approach is compatible with a wide variety of excitation sources, including ultrafast and broadband, and optical modalities. This allows an unprecedented degree of specificity, sensitivity, and selectivity with respect to functional features of materials systems, with nanometer spatial resolution and femtosecond temporal resolution. I will discuss several specific molecular and solid state systems which display some form of spatial inhomogeneity that can be probed with s-SNOM.

In addition, I will discuss the combination of plasmonic and optical antenna concepts with ultrafast and shaped laser pulses, to provide the precise control of an optical excitation on femtosecond time and nanometer length scales. I will present a new concept extending tip-enhanced spectroscopy into the nonlinear and ultrafast regime for background-free nano-scale imaging and spectroscopy, based on adiabatic nano-focusing on a tip. I will discuss the potential of this approach for implementing radiative decay engineering and coherent control.

9169-29, Session 7

Super-resolution confocal micrsocopy using optical saturation *(Invited Paper)*

Katsumasa Fujita, Nicholas I. Smith, Osaka Univ. (Japan); Shi-Wei Chu, National Taiwan Univ. (Taiwan); Satoshi Kawata, Osaka Univ. (Japan)

The recent development in optical microscopy has successfully overcome the limitation of the spatial resolution caused by the diffraction effect of light. Stimulated emission depletion (STED) and localization microscopy (FPALM/PALM/STORM) utilize the optical switching effect of fluorescence molecules to achieve the spatial resolution beyond the diffraction limit. Recently, we have proposed the use of saturated excitation (SAX) of fluorescence molecules to improve the spatial resolution of confocal microscopy. Since the saturated excitation introduces the nonlinear relation between excitation and fluorescence emission, detection of the nonlinear fluorescence responds allows us to reconstruct a fluorescence image with the improved spatial resolution. The nonlinear fluorescence signal is localized within the focal volume, therefore SAX microscopy can effectively suppress the background fluorescence signal, allowing us to observe a thick specimen, such as 3D-cultured cells, with the improved spatial resolution and image contrast. Since saturation is a fundamental phenomenon seen in any optical effect, SAX microscopy can also be applied to imaging techniques based on other optical phenomena, such as two-photon excitation. We recenlty observed the saturation effect in plasmonic light scattering from a gold nanopaticle and applied it to the super resolution imaging in metal particle observation.

9169-30, Session 7

Optical nanoscopy of a living cell *(Invited Paper)*

Balpreet S. Ahluwalia, Univ. of Tromsø (Norway); Deanna L. Wolfson, Frank Y. S. Chuang, Univ. of California, Davis (United States); Thomas R. Huser, Univ. Bielefeld (Germany)

Optical nanoscopy allows to study biological and functional processes of sub-cellular organelles. In structured illumination microscopy (SIM) the sample is illuminated with a grid-like interference pattern to encode higher spatial frequency information into observable Moiré patterns. By acquiring multiple images and a computation trick a super-resolved image is obtained. SIM provides resolution enhancement of 2X in each axis as compared to conventional microscopes. For a visible light, SIM provides an optical resolution of 100 nm. The challenges associated with optical nanoscopy of a living cell are photo-toxicity, special dye requirements and artifacts due to cell movement. SIM works with conventional dyes and is a wide-field technique making it suitable for imaging living cells. In this work, we will discuss the opportunities and challenges of imaging living cells using SIM. Two applications of optical nanoscopy of living cells will be discussed; a) imaging of mitochondria in a keratinocyte cell and b) cell-to-cell HiV viral transfection. Selective binding of stains was used for imaging sub-mitochondrial regions. Mito-Tracker stain was trapped inside the mitochondria consequently imaging mitochondrial compartments, whereas GFP-BacMan stains the mitochondrial membrane. For HiV work, the transfection of viral protein was successfully imaged from an infected Jurkat cell (Gag-iGFP expressing) to the primary CD4+T cells. The entire process of HiV transfection was imaged i.e. formation of viral synapse and the accumulation of viral protein at the cell membrane followed by the transfection of viral protein to the target cell.

9169-31, Session 7

Localized plasmon assisted structured illumination microscopy

Joseph L. Ponsetto, Feifei Wei, Zhaowei Liu, Univ. of California, San Diego (United States)

A new super resolution imaging method, i.e. Localized Plasmon assisted Structured Illumination Microscopy (LPSIM), is presented. Using a periodic hexagonal array of silver nanodiscs as localized plasmonic antennas, we vary incident laser polarization over a wide angle range to create dynamically tunable near-field excitations. For fluorescent samples placed on top of the antenna array, these excitations result in robustly changeable, finely structured illumination patterns. Since localized plasmons are confined to the dielectric-metal interface of the antennas, the antenna geometry alone limits the illumination pattern feature sizes, which enables a dramatic resolution improvement in comparison with the standard Structured Illumination Microscopy (SIM). Standard SIM schemes are limited to a 2X resolution improvement over the diffraction limit, because the structured illumination itself is diffraction limited. By leveraging the properties of localized plasmons, we untether ourselves from any propagating light or propagating surface plasmon dispersion limitations. This highly parallelizable approach allows for a wide field of view. The low number of sub-images required for reconstruction maintains the capacity for a high frame-rate. In full-wave simulations, recovered images for distributions of quantum dots as well as other non-sparse objects are presented, demonstrating high image quality and significant resolution improvement over existing methods. Based on Rayleigh criteria and full-width half maximum characterization, resolution of 51 nm (3X the diffraction limit) is shown. This resolution shown at safe visible frequencies holds promise for examining living cell dynamics at the nano-scale. The theory, design, and applications of this method will be discussed in detail.

9169-32, Session 8

Polarization analysis of the liquor films autofluorescence images to diagnose the time of death

Taras M. Boychuk, Bukovinian State Medical Univ. (Ukraine); Artem O. Karachevtsev, Yuriy Fedkovych Chernivtsi National Univ (Ukraine)

This paper presents the research results for diagnostic efficiency of a new azimuthally stable Mueller-matrix method applied to analyze the laser autofluorescence coordinate distributions of liquor films of the deceased.

A new model of the generalized optical anisotropy of biological films is offered to define processes of the laser autofluorescence. It is important to mention that influence of the complex mechanisms of both phase anisotropy (linear birefringence and optical activity), linear (circular) dichroism is taken into account.

The interconnections between the azimuthally stable Mueller-matrix elements characterizing laser autofluorescence and different mechanisms of optical anisotropy are determined.

The statistic analysis of coordinate distributions of such Mueller-matrix rotation invariants is proposed. Thereupon the quantitative criteria (statistic moments of the 1st to the 4th order) of determine the time of death.

9169-33, Session 8

Tunable phonon polaritons in van der Waals crystal of boron nitride

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Van der Waals heterostructures assembled from atomically thin crystalline layers of diverse two-dimensional solids are emerging as a new paradigm in the physics of materials. We use infrared (IR) nano-imaging to study the properties of surface phonon polaritons in a representative van der Waals crystal, hexagonal boron nitride (hBN). We launched, detected and imaged the polaritonic waves in real space and altered their wavelength by varying the number of crystal layers in our specimens. The measured dispersion of polaritonic waves was shown to be governed by the crystal thickness according to a scaling law that persists down to a few atomic layers. Our results are likely to hold true in other polar van der Waals crystals and may lead to their new functionalities.

9169-34, Session 8

Gas-metallic nanoparticle surface interaction characterized with in situ electron energy loss spectroscopy

John M. Kohoutek, Pin Ann Lin, National Institute of Standards and Technology (United States) and Univ. of Maryland, College Park (United States); Jonathan Winterstein, Henri Lezec, Renu Sharma, National Institute of Standards and Technology (United States)

We use an environmental scanning transmission electron microscope (ESTEM) equipped with electron loss spectroscopy (EELS), a monochromated electron source, and a custom-built gas flow cell to perform energy loss measurements on metallic nanoparticles (NPs) exposed to a local gaseous environment at varying pressures.

In particular, we characterize the effect of exposure to CO or H2 (at partial pressures of 10 Pa, 100 Pa, and HV) on the localized surface-plasmon-resonance (LSPR) of an Au NP. By addressing various sites around the perimeter of a triangular Au NP (edge length ~ 20 nm) with the electron beam in STEM mode, the energy loss spectrum resulting from site-specific excitation of LSPR is probed with a spatial resolution of ~ 1 nm and energy resolution of ~100 meV.

Local gas adsorption is evidenced by peak shifts in the energy loss spectrum, which are found to be positive for CO and negative for H2. Strong site selectivity is evident, with CO and H2 adsorbing preferentially at edge and corner sites, respectively.

To characterize the sign and magnitude of the energy shifts, finite-difference-time-domain (FDTD) simulations of electron-beam excitation of the NP are performed using a Drude model in which the local electron concentration is allowed to vary spatially over the particle volume. This is a result of both and the inhomogeneous spatial distribution of the adsorbate and its degree of electronegativity. An excellent match to experimental results is obtained for the respective cases of site-specific adsorption of CO, which is electropositive, and H2, which is electronegative.

9169-35, Session 8

Fourier-Stokes polarymetry of linear and circular birefringence of woman reproduction system tissues

Artem Karachevtsev, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

This paper presents the results of:

• Analytical reasoning of ability of spatial-frequency Stokes polarymetry method for mechanism phase anisotropy selection of structured fiber networks of histologic biological tissue sections .

• Experimental ability of linear and circular birefringence manifestation of fiber networks of benign and malignant tumors of womb side, on basis of spatial-frequency selection of azimuthally-stable Mueller-matrix images.

• Development abstract method of polarization reconstruction of phase anisotropy parameters of phase anisotropy in histological sections of biological tissues with spatial-frequency separation their visualization.

• Experimental realization present method in differentiation of anisotropy parameters of polycrystalline networks in case of oncological pathology severity –“pre-cancer- cancer” of women reproductive system parts.

• Generalization and approbation of Fourier methodology of azimuthally-stable polarization mapping of diffuse radiation field by human skin of laser radiation in distant diffraction zone.

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9170-1, Session 1

High-sensitivity silicon nanowire phototransistors *(Invited Paper)*

Siew Li Tan, Xingyan Zhao, Yaping Dan, Univ. of Michigan-Shanghai Jiao Tong Univ. Joint Institute (China)

Silicon nanowires (SiNWs) have emerged as a promising material for high-sensitivity photodetection in the UV, visible and near-infrared spectral ranges. The majority of SiNW photodetectors reported to date are mainly composed of either the photoconductor or PN junction photodiode structure. In this work, we demonstrate novel planar SiNW bipolar phototransistors on silicon-on-insulator (SOI) substrate using CMOS-compatible processes. The nanowires were patterned by electron beam (e-beam) lithography followed by metal contact evaporation, and subsequently etched by inductively coupled plasma reactive ion etching (ICP-RIE). The bipolar phototransistor consists of a PNP structure along the nanowire axis with an optically-injected base region. The doping densities of the active regions were defined by ion implantation using thick PMMA e-beam resist film as masks. The dopants were activated by rapid thermal annealing. We investigate the electronic and optical properties of the SiNW phototransistors by changing the active-region lengths and passivating the nanowire surfaces. Preliminary numerical device simulation shows that the optically-injected base photocurrent is amplified by over 2 orders of magnitude and that surface recombination velocity of the nanowire has a considerable effect on the gain. Compared with conventional bulk Si devices, the SiNW phototransistors are expected to offer the advantages of lower operating power and noise than avalanche photodiodes, higher sensitivity than Si photodiodes, as well as improved high-frequency response over bulk Si phototransistors.

9170-2, Session 1

Thermo-active behaviour of ethylene vinyl-acetate | MWCNT composites examined by in situ NEXAFS

Eva M. Campo, Bangor Univ. (United Kingdom)

Carbon nanotubes (CNTs) have garnered considerable interest in a wide range of academic fields, owing to their extraordinary mechanical, thermal, electronic and optical properties. CNTs are attractive candidates as fillers in composite materials, considerably improving the properties of the host. Recently, vast research has focused on the active properties of certain polymer-CNT composites. Development of this field is hindered by the absence of a unified actuation model explaining the molecular mechanics of these phenomena. Consequently, there is no method to predict whether specific materials exhibit this “smart behaviour”.

Near edge X-ray absorption fine structure (NEXAFS) spectroscopy is a valuable synchrotron technique for the study of nanocomposites, offering a wealth of information about local chemistry of the system, all with excellent energy resolution. Additionally, the use of a highly polarized beam allows for assessment of conformational arrangement of soft matter, which is of critical importance when the system is governed by non-covalent interactions.

In this study, temperature-dependence of thermally active ethylene-vinyl acetate (EVA) | MWCNT films are studied through in-situ NEXAFS spectroscopy. The effects of straining to promote CNT alignment and the role of dispersants are also addressed. Systematic variations in π^* C=C and π^* C=O were analysed and correlated with mechanical actuation at the macroscale. An actuation model based on CNT torsional effects is finally proposed, supporting our findings.

9170-3, Session 1

Light extraction enhancement of vertical LED by growing ZnO nano-rods on tips of n-GaN pyramids and polarization dependent measurement of nano-structure

Yen-Ju Wu, Cheng-Yi Liu, Chin-Han Liao, National Central Univ. (Taiwan)

Creating a textured pyramidal structure on the emitting n-GaN surface of the vertical GaN-based LED by wet-etching is considered to be the most effective approach for enhancing the light extraction efficiency of the vertical GaN-based light-emitting diodes (LEDs). The present study shows that the light extraction efficiency of the pyramidal n-GaN surface can be further enhanced by growing ZnO nano-rods on the n-GaN surface.

In addition, we find that the growth location of the ZnO nanorods on the n-GaN surface by hydrothermal method is highly correlated with the polarity of the n-GaN surface. By manipulating the polarity of the pyramidal n-GaN surface and water-dissolution process, ZnO nanorods can be specifically grown on the tips of the pyramids. With the tip-only ZnO NRs on the pyramidal n-GaN emitting surface, the light-output power of LED with a pyramidal n-GaN surface can be remarkably further enhanced by 49.6% at 250 mA. The correlation between the ZnO nanorods and polarity of the growing surface is studied by X-ray absorption spectroscopy (XAS). Thus, using the XAS analysis, we will demonstrate the correlation between the growth and the dissolution of nanostructure of the ZnO with the polarity of the ZnO c-plane surface, surface termination, and surface activity. The detail optical characterization of the vertical thin-GaN LEDs with ZnO NRs and its polarization dependent measurement would be present and discussed in this talk.

9170-4, Session 1

PbS quantum dot sensitized InGaZnO metal oxide hybrid phototransistor for near infrared detection

Do Kyung Hwang, Korea Institute of Science and Technology (Korea, Republic of); Hee Sung Lee, Yonsei Univ. (Korea, Republic of); Yun Jae Lee, Won Kook Choi, Korea Institute of Science and Technology (Korea, Republic of); Seongil Im, Yonsei Univ. (Korea, Republic of)

Colloidal quantum dots (QDs) are an important class of new materials due to their unique physical properties. In particular, PbS QD has great potential for optoelectronic applications because it is highly desirable as light absorber for near-infrared (NIR) detection. InGaZnO (IGZO) metal oxide is a promising alternative to amorphous or poly silicon technologies, which can facilitate the development of microelectronic or optoelectronic circuit systems on glass and flexible substrates. Here, we propose new hybrid approach of two emerging classes of PbS QD as light absorber and IGZO as the charges transport layer to create a bi-functional optoelectronic device application. The PbS QD can be functionalized directly onto the surface of IGZO TFT to produce a gate tunable, highly sensitive, and easily integrated PbS sensitized IGZO hybrid phototransistor for NIR detection. This hybrid phototransistor exhibits significant photo-induced threshold voltage shifts in the spectral range of 1400 - 700 nm, resulting in state-of-the art photoresponsivity over 103 A/W and specific detectivity on the order of 1014-1015 Jones. To further evaluate real potential towards optoelectronic circuit system, a photo gating resistive-load inverter is implemented by connecting a unit phototransistor to an external load resistor. The photo-induced

threshold voltage shifts of the hybrid phototransistor lead to a certain static or dynamic output voltage signal from our photo-gating inverter. We expect that this hybrid phototransistor can be simply integrated on glass or plastic substrates that can be applied to pixels on flat panel photo imaging applications or building blocks on complex photo gating logic circuits.

9170-5, Session 1

Heterojunction of nano-poly (O-toluidine) on silicon nanowires is investigated as a candidate heterojunction diode

Salah E. El-Zohary, Univ. of Tokushima (Japan) and Tanta Univ. (Egypt); Mohamed Shenashen, Akinori Tsuji, Toshihiro Okamoto, Masanobu Haraguchi, Univ. of Tokushima (Japan)

A heterojunction of Nanostructured conducting polymer poly O-toluidine (NPOT)/ silicon nanowires (SiNWs) is investigated as a candidate heterojunction diode. For this purpose, NPOT and NPOT/ SiNWs heterojunction is fabricated through economical cheap and simple techniques. I-V measurements of the device are made at room temperature under dark conditions. The heterojunction diode parameters such as turn on voltage, reverse saturation current (I0), ideality factor (ζ), barrier height (ϕB) and series resistance(Rs) are determined from I-V curves using Schottky equations. These values of these parameters are also extracted and verified by applying different methods of calculation. Compared to conducting polymers such like polyaniline or polyperrole on porous silicon heterojunctions mentioned in many research papers in literature, our proposed heterojunction expected to promise a novel heterojunction diode and hybrid solar cell. The reason may be understood as the aligned one-dimensional nanowire arrays offer a promising substrate providing a direct pathway for charge transport and high mobility for carriers. Also it was reported that SiNWs could play an important role in providing a large effective junction area which could help in light trapping helping in solar cell applications. In addition, we believe that in situ polymerization method, the chemical method used here is able to make a good coverage above and in interspaces of the fabricated SiNWs. This give good coverage compared the spin coating method which usually used. Good coverage is needed to fabricate a valuable and good heterojunction beween the conducting polymer and the Si nanostructures.

9170-6, Session 1

Transparent self-assembled InGaZnO thin film transistors with SiO_2-based solid electrolyte dielectric

Yuanjie Li, Xi'an Jiaotong Univ. (China); Yanghui Liu, Ningbo Institute of Materials Technology & Engineering (China); Wenci Sun, Xi'an Jiaotong Univ. (China)

Transparent amorphous oxide semiconductors (TAOS) have attracted considerable technological interests because of their high mobility (10-30 cm2/Vs), large-area uniformity and low temperature deposition capability. In particular, amorphous InGaZnO (a-IGZO) is regarded as a promising active channel material for flexible thin film transistors (TFTs)-driven display and sensors. In this work, TFT devices with the bottom gate structure have been fabricated with solid electrolyte nanocolumnar SiO2 film of ~800 nm by plasma-enhanced chemical vapor deposition (PECVD) as the gate dielectric layer on indium-tin-oxide (ITO) glass substrates. The ITO/SiO2/IZO capacitor structure was also fabricated to characterize the capacitance-frequency properties of SiO2 gate dielectric. A nickel shadow mask was placed directly above the SiO2 dielectric layer with a distance of ~50 μm. Subsequently, a 147 nm thick IGZO layer was sputtered on the SiO2/ITO/glass substrate using a commercial IGZO target (In:Ga:Zn=2:2:1 mol%) at room temperature by RF sputtering. During deposition, the IGZO layer diffracts into the shadow region of the nickel mask and a thin IGZO channel layer is self-assembled simultaneously. Optical transmission spectra of the TFT arrays on glass substrates were characterized using a UV/Visible spectrometer system. The electrical characteristics of the devices were measured by a Keithley semiconductor parameter analyzer and precision impedance analyzer in dark. Enhancement-mode IGZO/SiO2/ITO transparent TFT devices with field effect mobility of 10.5 cm^2/Vs, VT of 0.7 V, subthreshold swing (SS) of 70 mV/dec and Ion/off of 1.5x10^6 have been achieved in this work.

9170-7, Session 1

Characteristic temperature analysis for PbSe/ PbSrSe multiple quantum well structure

Majed Khodr, American Univ. of Ras Al Khaimah (United Arab Emirates)

The characteristic temperature calculations and dependency on cavity length was analyzed for Pb0.934Sr0.066 Se multiple Quantum well Structure at three temperature ranges 77< T<150 K, 150< T<300 K, and 77< T<300 K. In this work, we show the behavior of the characteristic temperature as a function of cavity length and were able to best fit the data to a second degree polynomial. Inclusion of theoretical values for the quantum efficiency due to Auger recombination reduces the characteristic temperature T0 in these ranges. It was found that inclusion of the quantum efficiency decreases the characteristic temperature by a factor of 0.6 for a wide range of cavity lengths. When results were compared to experimental data, it was concluded that there is a leakage current above the barrier due to thermionic emission. The leakage current density was estimated to be around 5423 A/cm2 at room temperature. With this high value more work is needed to understand the thermionic emission process to improve on the performance of this material system and similar ones.

9170-8, Session 2

Mechanical behavior of microelectromechanical microshutters

Devin E. Burns, Justin S. Jones, Mary J. Li, NASA Goddard Space Flight Ctr. (United States)

Microelectromechanical based microshutters are optically transmissive elements with high open/close contrast ratios (>10,000), high fill factors (>70%), and the ability to cover large optical fields of view, which can provide significant performance improvements for optical, IR, and UV instruments. Microshutters developed for the James Webb Space Telescope require magnetic actuation, which adds mass and increases complexity. Recently, electrostatically actuated microshutters have been developed and demonstrated under laboratory conditions. Electrostatic actuation eliminates the magnetic drawbacks, and may make microshutters more broadly available for space and ground based applications.

Successful electrostatic actuation is predicated on low drive voltages achieved by increasing capacitive forces or reducing microshutter stiffness. For microfabrication practicality and to maintain shutter sizing (resolution), shutter stiffness was lowered by reducing the structural layer thickness. In the current work, we present a micro-mechanical test system capable of measuring the microshutter stiffness and structural properties of related test structures. This system was validated using micro-cantilever beam test structures by comparing their deflection to beam theory predictions. Tests on microshutters consist of data from two design layups; one with 250 nm and one with 500 nm of Si3N4 as the primary structural layer (both also have 200 nm Al). The thicker microshutters were observed to be approximately 4 times as stiff; with a stiffness of 47 nN/micron versus 12 nN/micron. These results were found to be in good agreement with an analytical model and a finite element model which will be used to guide future design modifications.

9170-9, Session 2

Nanotube liquid crystal-elastomers: birefringence, flexible energy conversion, and photomechanical response

Balaji U. Panchapakesan, Xiaoming Fan, Univ. of Louisville (United States)

Rubber composites based on nanotube liquid crystals offer anisotropic physical properties and flexible energy conversion. Combining carbon nanotube liquid crystals with elastomers here in we demonstrate high optical anisotropy and photomechanical response of such composites to near infra-red excitation that is orders of magnitude larger than the pristine polymer. On NIR excitation, with application of small or large pre-strains significant expansion or contraction of the sample occurs respectively that is continuously reversible. Polarization microscopy revealed birefringence of transparent nanotube liquid crystal rubber composites with aligned domains turning light or dark through rotation of the polarization of linearly polarized light. Domains size was observed to exponentially decrease with increase in nanotube film concentration. The amount of carbon nanotubes used to fabricate the liquid crystal actuators was about ~300-700 times smaller than nanotube and graphene based photomechanical actuators reported till date. Extraordinary opto-mechanical response of ~10 MPa/W for ultra-small amounts of nanotube liquid crystals, high degree of transparency, anisotropic optical properties, and reversible stimuli responsivity of composites makes liquid crystals of nanotubes and elastomers as a new system that is important for soft actuation, energy conversion and photo-origami applications. Energy conversion efficiencies of ~1000 times greater than reported light driven piezoelectric polymer systems is reported for nanotube liquid crystal rubber composites.

9170-10, Session 2

Photothermal nanopositioners based on graphene composites

Balaji U. Panchapakesan, Univ. of Louisville (United States)

The addition of nanomaterials to polymers can result not only in significant material property improvements, but also assist in creating entirely new composite functionalities. By dispersing graphene nanoplatelets (GNPs) within a polydimethylsiloxane matrix, we show that efficient light absorption by GNPs and subsequent energy transduction to the polymeric chains can be used to controllably produce significant amounts of motion through entropic elasticity of the pre-strained composite. Using dual actuators, a two-axis sub-micron resolution stage was developed, and allowed for two-axis photo-thermal positioning (100 micro-meter per axis) with 120 nm resolution (feedback sensor limitation), and ~5 micro-meter/s actuation speeds. A PID control loop automatically stabilizes the stage against thermal drift, as well as random thermal-induced position fluctuations (up to the bandwidth of the feedback and position sensor).

Maximum actuator efficiency values of ~0.03% were measured, approximately 1000 times greater than recently reported for light-driven polymer systems.

9170-11, Session 2

Progress towards a MEMS tunable infrared filter using porous silicon

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Porous silicon is a very promising material for photonics and micromechanical applications. Etched from a silicon substrate, porous silicon can be adjusted to have an index of refraction from just below that of bulk silicon (nSi~3.5) to below that of silicon oxide (nSiO2~1.5). This property allows the formation of either well-defined discrete layers with controlled thicknesses and refractive indices, or films with a continuous variation of the index of refraction. The ability to control porosity, and therefore the index of refraction, allows for the creation of extremely highly reflective and wide bandwidth distributed Bragg reflectors (DBRs). In this work, we investigate porous-silicon distributed Bragg reflectors for spectroscopy in the mid-wave infrared (MWIR, 3-5 um) and long-wave infrared (LWIR, 7-12 um) wavelength ranges, and progress towards applying these reflectors in a tunable MEMS filter. Our design would provide wide tunability in the MWIR and LWIR regions. Utilization of porous silicon eliminates stress-related mechanical deformations unavoidable with deposited thin films. DBRs with reflectivity above 95% were etched, with reflectivity bandwidth covering either the entire MWIR or LWIR ranges. By spacing a thin cavity layer between two DBR's, an extremely narrow bandpass optical Fabry-Perot filter can be fabricated. With the addition of either thermal or mechanical tuning, these devices can be used for hyperspectral sensing and imaging, as well as for infrared molecular spectroscopy and chemical sensing.

9170-12, Session 2

Mid-infrared opto-nanofluidics for label-free on-chip sensing

Pao T. Lin, Massachusetts Institute of Technology (United States); Sen W. Kwok, Hao-Yu Lin, Harvard Univ. (United States); Vivek Singh, Lionel C. Kimerling, Massachusetts Institute of Technology (United States); George M. Whitesides, Harvard Univ. (United States); Anuradha Agarwal, Massachusetts Institute of Technology (United States)

A mid-infrared (mid-IR) label-free chemical sensor was developed using opto-nanofluidics consisting of a Si-liquid-Si slot-structure. A broadband mid-IR lightwave can be strongly confined within a nanofluidic capillary by utilizing the large refractive index contrast ($\Delta n \sim 2$) between the liquid core waveguide and the Si cladding. Through an optical-field enhancement together with a direct interaction between the probe light and the analyte, the sensitivity for chemical detection is increased by 50 times when compared to evanescent-wave sensing. This spectral characterization distinguished several common organic liquids (e.g., n-bromohexane, toluene, isopropanol) accurately, and could determine the ratio of chemical species (e.g., acetonitrile and ethanol) at low concentration (< 5 µL/mL) in a mixture through spectral scanning over their characteristic mid-IR absorption peaks. The combination of CMOS-compatible planar mid-IR microphotonics, and a high-throughput nanofluidic sensor system, provides a unique platform for chemical detection.

9170-13, Session 3

Keeping x-ray eyes on nanoparticles synthesis in the solution – in-situ diffraction and absorption studies *(Invited Paper)*

Malwina Staniuk, Markus Niederberger, Dorota Koziej, ETH Zürich (Switzerland)

Nowadays, materials utilized in energy-related application exhibit the hierarchical architecture.[1] However, their superior functionalities are related to the intrinsic properties of nanoparticles and effects induced by the interaction between the individual building blocks. Thus, a formidable challenge is the intimate mixing and assembling of the components into complex structures and a good deal of work is still required to optimize and extend them to practical usage. An attractive method is a direct synthesis of multicomponent/hybrid structures in the solution. Therefore, we are particularly interested in controlling and understanding complexity of the solution-based reactions. We follow the processes of transition

from inorganic molecule of precursor to crystalline nanoparticles by means of in-situ synchrotron based X-ray absorption spectroscopy and X-ray diffraction. We show different mechanisms leading to the crystal structure transition in the solution: (a) driven by increasing size of nanoparticles, (b) driven by time dependent kinetics and (c) driven by catalytic reactions of products.[2-3] Additionally, we shed light on ways to access the interdependence between the changes of the oxidation state of precursor and the several parallel reactions leading to nucleation and growth of nanoparticles. These results are fundamental on the way to control oxidation states in liquid-phase synthesis of nanoparticles.[3]

[1] Koziej et al. Adv. Mater. 26 (2) 2014, 235–257

[2] Koziej et al. Small 7 (3) 2011, 377-387

[3] Staniuk et al. submitted 2014

9170-14, Session 3

Optical characterization of CMOS compatible micro optics fabricated by mask-based and mask-less hybrid lithography

Sunglin Wang, Chris Summitt, Lee Johnson, Melissa A. Zaverton, Thomas D. Milster, Yuzuru Takashima, The Univ. of Arizona (United States)

Silicon photonics devices offer a promising solution for the integration of optical data transmission technology into local computer peripheral devices. However, the implementation has not yet been perfected due to the difficulty of coupling light across multiple levels. One possible implementation is through the fabrication of an optical via, or optical path perpendicular to the surface of the integrated photonics chip. In order to fabricate an optical via which will integrate multiple levels in a silicon photonics device, mask-less lithography can be used together with a familiar packaging material. As a crucial component for the optical via, an in-plane light coupler by which the direction of the light is bent in 90 degrees is needed. This coupler should be fabricated using a CMOS compatible material and process without wet or dry etching to avoid additional cleaning processes. For the purpose, buffer coat material can be used to fabricate a mirror-based coupler by using conventional mask-based lithography followed by mask-less hybrid lithography. The hybrid process allows fabrication of a well-defined structure with arbitral shape such as micro mirrors at designated location on the chip for example next to waveguides. We report fabrication and characterization of the optical property of the 45 degree micro mirror. Surface angle and roughness are evaluated by an interferometer. The result agrees with inspection by the other methods such as cross sectional scanning electron microscope. Experimental evaluation of optical efficiency of the system including the mirror for routing of the laser beam in 90 degree will be addressed.

9170-15, Session 3

High efficiency photonic hierarchical nanostructures self-assembled from the gas phase

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The increasing awareness of industries in the commercial opportunities given by nanotechnology is driving the research and development of novel material designs with cutting edge functionalities. Nature, with several billion year of R&D, has often been taken as example to derive smart solution to engineering problems. In the field of optics the natural world molds the flow of light with wide variety of nanometer scale modulations of materials properties, like porosity and morphology (e.g. cuticle of the beetles, butterfly wings or mother of pearls). Being able to mimick these strategies with added high-tech functionalities would open up a broad array of applications. Existing fabrication techniques of porous photonic architectures severely limit their exploitation. Here we report on photonic hierarchical nanostructures obtained by self-assembly from the gas-phase at low temperature. Periodic refractive index modulation is achieved by stacking layers with different nano-architectures. Fine control over material density and porosity allows the fabrication of high efficiency ($R(\lambda) > 85\%$) single material photonic crystal with tuneable Bragg-diffraction peak. The fabrication of high efficiency broad band dielectric mirrors ($R \approx 1$ over the whole visible spectum) on glass and flexible substrates, opto-fluidic switches and matrix of photonic crystal pixels with feature size < 10 micron is demonstrated. Porous photonic crystals fabricated with conductive, semiconductor and insulating materials are shown to withstand temperature (>500°C) common in silicon platform. This new technique is demonstrated to be a promising route for filtering, optical-sensing, electro-optical modulation, light harvesting energy devices and photocatalysis applications.

9170-16, Session 3

Near-edge x-ray absorption fine structure studies of electrospun poly(dimethylsiloxane)/poly(methyl methacrylate)/multiwall carbon nanotube composites *(Invited Paper)*

Eva M. Campo, Bangor Univ. (United Kingdom)

Near-edge X-ray absorption fine structure (NEXAFS) spectroscopy provides a wealth of information about local bonding, chemical environment, and conformational configuration of a system, rendering the technique an attractive tool in the study of nanocomposites. In this work, NEXAFS spectroscopy is used to analyse electrospun Poly(dimethylsiloxane) (PDMS) /Poly(methyl methacrylate) (PMMA) / Multiwall Carbon Nanotube (MWCNT) nanocomposites.

Critical to electrospinning and general nanocomposite design and synthesis, this work addresses alignment of fibres and polymeric chains, as well as fillers. Spectra acquired with composite fibre direction parallel and perpendicular to the beam polarisation suggested a simple electrospinning setup was not sufficient to align polymeric chains uniaxially. Though polymer phase segregation was observed in SEM, NEXAFS spectra revealed good composite homogeneity. Strong conformational effects were observed, however, in angular resolved NEXAFS spectra.

Nanofiller size was observed to greatly influence composite spectra. Emissions attributed to C-H and C=O groups were most significantly altered on addition of filler, suggesting their importance in interfacial bonding. Finally, proposed bonding models of non-covalent CH-π interactions and hydrogen bonding are discussed.

9170-17, Session 3

Rate-dependent viscoelastic contact of polymeric materials in transfer printing

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This work presents a multiscale computation of decohesion or debonding in transfer printing between silica and cross-linked poly-dimethlysiloxane (PDMS). We employed the interfacial cohesive zone law obtained from the atomic interactions at the interface between the PDMS and silica (Smith et al, 2004 and 2007) to analyze the macroscopic mechanical system of Jang et al (2011). The interfacial cohesive law is coarse-grained with the aid of the relaxation method (Nguyen and Ortiz, 2002), and utilized for a FE analysis of the transfer printing process. The PDMS is considered as a viscoelastic elastomer with its instantaneous deformation behavior being described as a hyperelastic material. Ogden's

hyperelasticity model is considered, and finite strain viscoelasticity is implemented consistent with the hyperelasticity.

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9170-18, Session 4

Power delivery and self-heating in plasmonic nanoscale devices

Nan Zhou, Luis M. Traverso, Xianfan Xu, Purdue Univ. (United States)

Plasmonic devices, made of nanoapertures or nanoantennas, have played significant roles in advancing the fields of optics and opto-electronics by offering subwavelength manipulation of light in the visible and near infrared frequencies. For example, in optical near-field nanolithography, nanostructured plasmonic len has been chosen as the focusing element. The development of heat-assisted magnetic recording (HAMR) opens up a new application of plasmonic nanostructures, where they act as near field transducers (NFTs) to locally and temporally heat a sub-diffraction-limited region in the recording medium to reduce the magnetic coercivity. Generally, for these applications, plasmonic nanostructures should simultaneously deliver enough power to certain targets with as small as possible incident laser power to reduce the self-heating effect, which could lead to degradation of performance and failure of the device. In this work, we study the effect of material properties on the coupling efficiencies of different nanoaperture-based designs and the corresponding energy dissipation. We will show the limitations of common metallic materials as a result of self heating. The possibility of using alternative or ideal plasmonic materials for delivering higher power and/or reducing heating in these plasmonic nanostructures will be discussed.

9170-19, Session 4

Directly deposited plasmonic metasurface for omnidirectional visible super absorption

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Plasmonic metamaterial super absorbers are emerging as attractive candidates for photo-harvesting, surface enhanced biosensing, photocatalysis, and thermal energy recycling. However, most of reported meta-absorbers with periodic nanopatterns were fabricated using expensive and low-throughput top-down nano-lithography techniques, therefore imposing a serious cost barrier for the development of practical applications. Additionally, other alternative methods such as chemical synthesis and nanostencil lithography are so complicated that technical barriers still exist to obtain high-quality and large-area metallic nanopatterns. We here report a simple, scalable and cost-effective method to manufacture uniform super absorptive metasurfaces in large areas using a direct tilted-sputtering technique. Using this technique, densely packed metallic nanopatterns with controllable size distributions can be easily formed on either rigid or flexible substrates. These metallic nanopatterns were then covered sequentially by an ultrathin dielectric film and optically-thick metallic ground plate to constitute designed three-layered meta-absorbers. A remarkable optical absorption peak over 96% in the visible regime was obtained successfully which is insensitive to polarization states and incident angles up to 70º. Moreover, the lateral dimension of these random nanopatterns can be tuned further by post thermal annealing processes, resulting in a wide spectral tunability of the super absorption resonances in the visible-to-near-infrared domain. This omnidirectional, polarization-insensitive super absorber structure is particularly promising for the development of novel thin-film energy harvesting devices, all-angle color filters and biomimetic photonic structures.

9170-20, Session 4

Effects of different wetting layers on the growth of smooth ultra-thin silver thin films

Chuan Ni, Piyush J. Shah, Andrew M. Sarangan, Univ. of Dayton (United States)

Ultrathin silver films (thickness below 10 nm) are of great interest as optical coatings in low-emissive windows and plasmonic devices. However, producing these films has been a continuing challenge because of their tendency to form clusters rather than smooth contiguous thin films. In this work we have studied the effect of Cu, Ge and ZnS as wetting layers (1.0 nm) to achieve ultrasmooth ultrathin silver films. The silver films (5 nm) were grown by RF sputter deposition on silicon and glass substrates using a few monolayers of the different wetting materials. SEM imaging was used to characterize the surface properties such as island formation and roughness. Also the optical properties were measured to identify the optical impact of the different wetting layers. Finally, a multi-layer silver based structure is designed and fabricated, and its performance is evaluated. The comparison between the samples with different wetting layers show that the designs with wetting layers which have similar optical properties to silver produce the best overall performance. In the absence of a wetting layer, the measured optical spectra show a significant departure from the model predictions, which we attribute primarily to the formation of film clusters.

9170-22, Session 4

Simulation of a film of random particulate medium containing aggregates of metal nanospheres

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We dispersed silver nanospheres of diameter 5nm in a homogeneous binder. Films were spin-coated on glass substrates. The transmission spectra of such films are measured as particle concentration is varied. The transmission spectra show deeper and wider minima in the shorter wavelength side as the concentration of nanoparticles increase. This might be explained by the formation of aggregates of nanoparticles and the coherent interaction among the constituent elements of the aggregates. The coherent interaction can include excitation of the modes due to coupling of localized surface plasmon resonance (LSPR) modes of individual particles. To explain the dependence of transmission spectra on the concentration of particles we computed the scattering properties of particle aggregates [1].

The scattering properties of a single spherical particle can be computed

analytically using Mie theory. No analytical computation method is available for aggregates of nanoparticles. Numerical methods, like finite-difference time-domain (FDTD) method can be used.

We computed the scattering properties of aggregates of silver nanospheres using a three dimensional monochromatic version of recursive convolution finite-difference time-domain (RC-FDTD) method [2]. In contrast with the conventional broadband RC-FDTD [3], the monochromatic version allows one to use the handbook values of permittivity of the material of the particles at every simulation wavelength. The algorithm employs the 1st order Drude model [3] to make it stable for metals with negative real part of permittivity. The particle-aggregates are generated using a random number generator that distributes nanospheres uniformly throughout a larger sphere made of the homogeneous binder medium.

9170-23, Session 4

Spin Hall effect of light reflected from an air-magnetic thin film interface

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The displacements for |P> polarization (electric field parallel to the plane-of-incidence) and |S> polarization (electric field perpendicular to the plane-of-incidence) induced by the spin Hall effect of light reflected from a magnetic cobalt thin film have been investigated. The significant differences from those of an air-glass interface are attributed to the special complex permittivity and refractive index of the cobalt film. The real part of the complex refractive index has more influence on displacements for |P> polarization than for |S> polarization. There also exists a particular incident angle corresponding to the zero displacement for |P> polarization. It shifts from 52 to 76 degree when the real part rises from 1.0 to 4.0. For both |P> and |S> polarizations, the maximal displacements rapidly rise with the decrease of the imaginary part. Our simulations further demonstrate that polarization-insensitive spin separations can be realized by choosing the medium with an optimal permeability.

9170-24, Session 5

Monolithic mode-locked lasers based on high finesse silicon ring resonators

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Low noise mode-locked lasers and stabilized optical frequency combs are receiving considerable attention due to their broad spectrum of applications that ranges from signal processing and communications to metrology. Progress has been made in the realization of ultralow noise pulse trains that are used as sampling pulses for analog to digital converters from electrically efficient and compact semiconductor gain media. However, these realizations require ultralow expansion (ULE) quartz etalons for filtering the axial mode groups, making miniaturization difficult. Further advances are needed to reduce the size of these sources so that a chip-scale footprint can be achieved to enable new applications. One important step towards miniaturization is the integration of a high finesse optical filter that would serve to replace the ULE etalon.

In this talk, we report our experimental results towards the realization of a fully integrated mode-locked semiconductor laser. We present a high finesse and large FSR ring resonator capable of generating pulses at a repetition rate of ~32 GHz when is coupled to a semiconductor amplifier via a larger fiber loop. In addition, an intensity modulator incorporated in the fiber loop and modulated at the free spectral range of the ring resonator produces a stabilized mode-locked optical frequency comb. The performance specifications of this system will be presented and compared with state of the art etalon-based cavities for the realization of on-chip mode-locked lasers. We also present our recipe for fabricating large and low loss silicon ring resonators pertaining to this work.

9170-25, Session 5

Optimization of mode pattern and transmission analysis of GaN LED with ITO grating

Juliet Chico, Gabriela Aleman, Xiaomin Jin, California Polytechnic State Univ., San Luis Obispo (United States)

We study nano-ITO grating surface GaN LED to improve light extraction efficiency by optimizing the device parameters. We propose new study method which is optimization of mode pattern and transmission analysis of an LED. Modal and transmission analyses are performed on a gallium nitride (GaN) based light emitting diode to achieve maximum light extraction. Optimization is achieved when the cavity and waveguide modes are in their best condition, emitting waves that interfere constructively with the nano-grated LED, produced by the best grating case. The various structural effects of the nano-gratings on light transmission are investigated, thus concluding that the transmission efficiency has a strong dependence upon these structural effects brought forth by the parameters of the nano-grated structure. By varying the period, height, and width of the ITO grating, we generated a 69.42% efficiency increase in the light extracted compared to the non-grating case of 54.74%, which is a 27% improvement. The grating location is also investigated through modal analysis, which shows that the optical confinement factor (OFC) is greatly dependent on this parameter, reaching a maximum of 13.21%. With the improved grating location, a transmission analysis is performed, producing the light transmission of 81.88%, compared to the non-grating case of 55.89%, achieving a 47% improvement.

9170-27, Session 5

Construction of germanium nanowire and nanotube arrays by electrodeposition from an ionic liquid

Jiupeng Zhao, Xusong Liu, Yao Li, Harbin Institute of Technology (China)

Germanium have gained much attention as a promising semiconductor material and one-dimensional gemanium nanostructures both in the form of nanowire (NW) and nanotube(NT), are proven to be the most interesting structures due to their unique shapes and microstructures. Therefore it has significance and scientific value to explore a new method for construction 1D germanium arrays and to study their properties. Electrodeposition of semiconductors in ionic liquids shows its unique advantages. The arrays of germanium nanowires and nanotubes are constructed by using template assisted electrodeposition in ionic liquids for the first time. The composition and microstructures of 1D germanium arrays are studied in detail. The relationship of process parameters, compostion and microstructure are discussed in order to improve performances of the materials. The growth process and the mechnism of germanium NW and NT are also discussed.

9170-28, Session 5

Multi-cell design for III-N avalanche photodiodes

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GaN and AlGaN (III-N) avalanche photodiodes (APDs) are emerging as an alternative to current ultraviolet(UV) photodetector technologies based on UV enhanced Silicon, micro-channel plates, and photo multipliers. They promise high quantum efficiency, tunable cutoff wavelength, visible and solar blind detection without the use of filters , high operating temperature and high-energy radiation tolerance. These properties are highly sought after, for applications in missile warning systems, corona detectors, space imaging, spectroscopy and other advanced applications.

Current work in III-N APDs is based on the p-i-n and p-i-n-i-n Separate Absorption and Multiplication (SAM) design. This work describes a new design for III-N based APDs based on a parallel array of micron sized III-N mesas. The multicell architecture creates a non-uniform electric field across the device resulting in localized avalanches at a lower voltage compared to a single cell photodiode of equivalent area. The APD structures are grown on sapphire substrates using optimized III-N metalorganic chemical vapor deposition (MOCVD) processes, followed by patterning using a BCl3/Cl2 Inductively coupled plasma etch and regrowth of the p-layer. Devices with diameters ranging from 20 to 120?m are fabricated and characterized for dark current, gain, spectral responsivity and other APD performance metrics. The measurement results are compared with physics based simulations done using Synopsys TCAD.

9170-29, Session 5

Enhancement of laser damage resistance of high- and anti-reflective optical multilayers by tailoring the electric field distribution and post annealing

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High performance reflectors are well known in the literature, however it is difficult to manufacture in the broad band and uv region with metal deposition due to adhesion and protection problems. In our approach we developed different design with PVD method and discussed the way to solve problems. Additionally, results tested by MIL standards are presented.

9170-30, Session 5

VLSI photonics for lidar sensors

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We report on advanced VLSI photonic integrated circuits used for the production of light detection and ranging (LiDAR) sensors that enable real-time high-accuracy 3D mapping and object detection, tracking, identification and classification.

9170-31, Session 6

Ultra-high aspect ratio nanostructure fabrication using vertical directionality controlled metal assisted chemical etching *(Invited Paper)*

Anne Sakdinawat, Chieh Chang, SLAC National Accelerator Lab. (United States); Richard C. Tiberio, Stanford Univ. (United States); Michael J. Rooks, Yale Univ. (United States); Raymond Leung, Carl Zeiss X-ray Microscopy, Inc. (United States); Johanna L. Nelson Weker, SLAC National Accelerator Lab. (United States)

Vertical, directionality controlled metal assisted chemical etching (V-MACE), a method that can be used to fabricate ultrahigh aspect ratio, dense, nanoscale features, will be presented. Using V-MACE, we have fabricated high efficiency x-ray diffractive optics for the hard x-ray region for applications in x-ray microscopy, x-ray diffraction, and astronomy. Structures include x-ray Fresnel zone plates and spiral zone plates with aspect ratios ranging from 20:1 to greater than 100:1 aspect ratio with feature sizes currently ranging from 30 - 100 nm.

9170-32, Session 6

Nano fabrication of compound bifocal zone plate for x-ray optics

Armen V. Kuyumchyan, American Nanoscience and Advanced Medical Equipment, Inc. (United States); Alexey Y. Suvorov, Japan Synchrotron Radiation Research Institute (Japan)

The development of nanotechnology gives new possibilities for fabrication of different X-ray optical elements. The compound silicon crystal Zone Plate (ZP) is fabricated by an electron beam lithography and lift-off technology. ZPs structures have been etched by ion-plasma up to 6 µm deep. A linear ZP of the first and second orders fabricated for X-ray radiation 10 kev energy, the focal distance is 57sm. The experiment was performed at the beam line BL29XU Spring-8 of the Japan Synchrotron Radiation Facility. The experimentally and theoretically investigations were done for x-ray energy at the 10 KeV and 12.4 keV (0.1nm wavelength). Depending on the absorption of ZP; it can be: a) amplitude ZP, b) phase ZP, c) amplitude-phase ZP. The radial distribution of intensity is determined as a convolution of the zone plate transmission function and the Kirchhoff propagator in par-axial approximation. The algorithm is based on the FFT procedure and studied by means of computer programming simulation.

9170-33, Session 6

A spiral focusing vortex lens: shaping scalable orbital angular momentum of light

Hong Liu, A*STAR Institute of Materials Research and Engineering (Singapore); Muhammad Q. Mehmood, Kun Huang, National Univ. of Singapore (Singapore); Karen L. Ke, A*STAR Institute of Materials Research and Engineering (Singapore); Huapeng Ye, National Univ. of Singapore (Singapore); Patrice Genevet, Harvard School of Engineering and Applied Sciences (United States); Mingsheng Zhang, A*STAR - Data Storage Institute (Singapore); Cheng-Wei Qiu, National Univ. of Singapore (Singapore); Jinghua Teng, A*STAR Institute of Materials Research and Engineering (Singapore)

Recent developments have shown that light's orbital angular momentum (OAM) can be harnessed for a diversity of applications including optical manipulation, microscopy imaging, astronomy, quantum information, optical communication and remote sensing. The traditional vortex phase plate and recently-proposed metasurfaces are all discrete devices to generate Laguerre-Gaussian (LG) and higher-order Bessel beams of an intrinsic limitation—increasing the topological charge will lead to a dispersion of annular intensity followed by a lower photon density. To harness OAM in practice, for example, quantum entanglement, optical trapping and atom-level optical manipulation, optical vortex beam simultaneously carrying highly concentrated photons as well as substantial amount of OAM are in great demand. In this study, we demonstrate a spiral vortex lens to generate as well as focus optical vortex beam twisting around its beam-axis to follow a conical trajectory with the unique feature of a crescent-shaped intensity cross section, which is microscopically-confined and projected to as far as ~ 50? away in free space. Scalable OAM can be achieved simply by manipulating its radial and azimuthal factors. Due to the aperiodic and continuously variant nanostructure, it provides a compact solution to produce scalable OAM concurrently with highly concentrated photons through continuously modulating the amplitude and phase in the diffraction field. Comprehensive theoretical studies reveal that this fantastic property comes from the anisotropic inhomogeneity in the nanostructures, which governs the interaction of the spiral vortex lens with light over a broadband range. Acting as in-principle an inexhaustible-OAM turbine, this spiral focusing vortex lens has great potentials in optical manipulation, 3D light shaping, laser processing and photonics miniaturization.

9170-34, Session 6

Omnidirectional wavelength selective emitters/absorbers based on dielectric-filled anti-reflection coated two-dimensional metallic photonic crystals

Yi Xiang Yeng, Jeffrey B. Chou, Massachusetts Institute of Technology (United States); Veronika Rinnerbauer, Johannes Kepler Univ. Linz (Austria); Veronika Stelmakh, Yichen Shen, Sang-Gook Kim, Massachusetts Institute of Technology (United States); John D. Joannopoulos, MIT Institute for Soldier Nanotechnologies (United States); Marin Soljacic, Ivan Celanovic, Massachusetts Institute of Technology (United States)

We demonstrate designs of dielectric-filled anti-reflection coated (ARC) two-dimensional (2D) metallic photonic crystals (MPhCs) capable of omnidirectional, polarization insensitive, wavelength selective emission/absorption. Up to 26% improvement in hemispherical emittance/absorptance below the cutoff wavelength is observed for optimized hafnium oxide filled 2D Tantalum (Ta) PhCs over the unfilled 2D Ta PhCs. The optimized designs possess high hemispherical emittance/absorptance of 0.86 at wavelengths below the cutoff and low hemispherical emittance/absorptance of 0.12 at wavelengths above the cutoff, which is extremely promising for applications such as thermophotovoltaic energy conversion, solar absorption, and infrared spectroscopy.

9170-35, Session 7

A versatile platform for sp2-carbon substrate non-covalent functionalization by supramolecular self-assembly: towards applications in nanophotonics *(Invited Paper)*

André-Jean Attias, Ping Du, David Kreher, Fabrice Mathevet, Univ. Pierre et Marie Curie (France); Fabrice Charra, Commissariat à l'Énergie Atomique (France)

In view of the demanding forthcoming applications in nanotechnology, it is of prime interest to create functions out-off the plane and fully exploit the room above the substrate. Accessing the third dimension is so a mandatory step for nanooptics/electronics. Previously we introduced the Janus-like 3D tecton concept. It consists of a dual-functionalized unit presenting two faces linked by a rigid spacer: one face (A) is designed for steering 2D self-assembly, the other one (B) is a functional molecule. The objective is to take advantage of the in-plane self assembling of building blocks lying on face A to control the positioning of out-off plane active unit B, linked to the base by a rigid pillar. Here we present a series of Janus tectons incorporating chromophores ranging from fluorescent dyes to photoswitchable molecules. We will present the optical properties in solution as well as the properties of the self-assembled functional monolayers on sp2-hybridized carbon supports investigated by STM. The successful self-assembly on graphene, together with the possibility to transfer the graphene monolayer onto various substrates, considerably expends the domains of application of our functionalization strategy

9170-36, Session 7

Laser-assisted biosynthesis for noble nanoparticles production

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Extracellular Biosynthesis technique (EBS) for nanoparticles production attracted a lot attention as environmentally friendly and not expansive methodology. Our recent research was focused on rapid approach of the green synthesis method and achievement of reduction and homogeneous size distribution of nanoparticles by pulse laser application. Noble nanoparticles (NNPs) were produced using various ethanol and water plant extracts. The choice of plants in the present paper has been made based on their biomedical applications. In this paper, leaved plants such as Magnolia Grandiflora, Geranium, Aloe 'Tingtinkie', Aloe Barbadensis (aloe vera), Eucalyptus Angophoroides, Sansevieria Trifasciata, Impatiens Scapiflora, with water and ethanol extract, were used as reducing agents to produce nanoparticles. The reaction process was monitored using UV-Visible spectroscopy. NNPs were characterized by Fourier Transfer Infrared Spectroscopy (FTIR), Transmission Electron Microscopy (TEM), Dynamic Light Scattering technique (DLS). During the pulse laser Nd-YAG illumination (λ=1064nm, 532nm, PE= 450mJ, 200mJ, 10 min) the blue shift of surface plasmon resonance absorption peak was observed from ~424nm to 403nm for silver NP; and from ~530nm to 520 nm for gold NPs. In addition, NNPs solution after Nd-YAG illumination was characterized by narrowing of the surface plasmon absorption resonance band, which corresponds to monodispersed NNPS distribution.
FTIR, TEM, DLS, Zeta potential results demonstrated that NNPs were surrounded by biological molecules, which naturally stabilized nanosolutions for months. Cytotoxicity investigation of biosynthesized NNPs is in progress.

9170-37, Session 7

Nanoimpriont fabrication of wiregrids micro-polarizers in near infrared spectra using SU-8 as an intermediate film

Junxin Wang, Andrew M. Sarangan, Univ. of Dayton (United States)

Polarization imaging in the visible spectrum is an area of growing interest, but the technology to integrate pixel-level polarizers has proven to be difficult. A number of different techniques have been used in the past, but the least obtrusive method is to fabricate the wiregrids on a transparent substrate and hybridize it to the image sensor. Wire grids are most easily fabricated by lift-off lithography, but this comes at the expense of reduced aspect ratios and reduced optical extinction ratio. An attractive alternative is the damascene process, where grooves are first etched into a dielectric and then planarized with the desired metal. Although silica glass is the most desired substrate for visible applications, compared to silicon it is more difficult to process because of its poor photoresist etch contrast and adhesion. In this paper, we demonstrate a different technique for the damascene process where a polymer film on glass is used as the substrate for imprinting the grooves, followed by metallization and planarization. A high resolution 150nm periodic stamp is fabricated on silicon using deep UV (266nm) interference lithography and deep silicon etching. This nanostructure pattern is transferred onto a patternable epoxy (SU-8) using vacuum thermo-compression and in-situ UV exposure and thermal curing. SU-8 was chosen because it is optically clear and easily imprinted. Because of its mechanical properties, it is also durable and can withstand the planarization step. In this paper we will show the results from this process, including process details, SEM images and performance data.

9170-38, Session 7

Breaking the diffraction limit with photoinhibited superresolution lithography

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Photoinhibited superresolution (PInSR) lithography is a two-color, one-photon technique promising fast sub-diffraction limit patterning in the far-field. While previous work has shown that the method is susceptible to blurring from reactive species diffusion, we have recently successfully addressed the issue with a low-mobility methacrylate resist. Here we demonstrate superresolved patterns, with feature spacing 3x better than the 0.2 NA diffraction limit. To better understand the photocrosslinking resist used to generate these results, we propose new methods for probing reactive species concentration and polymerization dynamics at submicron scales. Experimental results help to guide the development and calibration of a coupled PDE kinetic model, which is also presented. Numerical simulations using the model are then used to further explore the system dynamics and inform efforts to improve resolution, photospeed and pattern fidelity.

9170-40, Session 8

Computational analysis of noble ZnO/MgO branched nanorod structure on V-LED with finite-difference time-domain method

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GaN based light emitting diode (LED) is one of the most promising solid-state lighting due to high efficiency and long life time. However, most of the generated photons are confined in the device due to its total internal reflection (TIR) and only 4.1% of photons can contribute to the efficiency. Many attempts are being made to improve the light extraction efficiency of GaN LEDs such as surface texturing, photonic crystals and nanostructures. However, these methods are expensive and show limits in increasing the light extraction efficiency. Another promising method is using ZnO nanorod structures on GaN LED as a light extraction layer. This showed enhancing up to 79% than flat LED in the light extraction, but this effect originating from size reduction (<100nm) of nanorod was not practical to make. Waveguide from the TIR also can be generated in ZnO nanorod so that makes limitation on enhancing light extraction. In this report, a ZnO nanorod on which MgO branches were grown on the side walls are designed to maximize the extraction of photons. The light extraction mechanism is analyzed by Finite-difference time-domain (FDTD) method which the far-field and electric-field distribution shows further extraction of the light wave-guided inside ZnO nanorod through MgO branches. Compared to ZnO nanorod, the optimized ZnO/MgO branched nanorod structure (radius 25nm, height 500nm MgO branches) enhanced extraction efficiency up to 68%.

9170-41, Session 8

Polarized light emission by deposition of aligned semiconductor nano rods

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The ability to control the position and orientation of nanorods (NRs) in a device is interesting both from a scientific and a technological point of view. Because NRs exhibit anisotropic absorption, and spontaneous and stimulated emission, aligning individual NRs to a preferred axis is attractive for many applications in photonics such as solar cells, light-emitting devices, optical sensors, switches, etc.

Electric-field-driven deposition from colloidal suspensions have proven to be an efficient method for the controlled positioning and alignment of anisotropic particles. In literature strong AC fields are combined with casting of single drops and subsequent drying of the solvent, which is not compatible with reproducible and homogeneous deposition on large substrates as required for large size applications such as solar cells or OLEDs. In this work, we present a novel technique for the homogeneous deposition and alignment of CdSe/CdS NRs on a glass substrate patterned with transparent indium tin oxide (ITO) interdigitated electrodes, with a spacing of a few micrometers. This method is based on applying a strong AC electric field over the ITO electrodes during the dip-coating procedure and subsequent evaporation of the solvent. The accumulation, alignment, and polarized fluorescence of the NRs as a function of the electrical field during deposition are investigated. An alignment with order parameter of 0.67 and a polarization ratio of 0.60 has been obtained.

9170-42, Session 8

Design of single-polarisation single-mode photonic nanowire

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Waveguides with sub-wavelength dimensions known as photonic nanowires have the potential in realizing single-polarization single mode (SPSM) fibers, which guide only one polarization state of fundamental modes, have greater advantages in polarization sensitive applications, such as fiber optic gyroscopes, fiber optic current sensors, high-power fiber lasers, and coherent optical communications.

In this paper, we have presented a novel design approach for realizing photonic nanowires that can deliver SPSM performance. By producing high anisotropies in the core and the cladding structure through the elimination of lines of air holes in the cladding while two air holes are removed as the core, a high birefringence which accounts for a broadband of SPSM transmission is obtained. Therefore, aiming to have a low confinement loss, eight air holes are enlarged surrounding the silica core region.

By applying the full-vector finite element method with an anisotropic perfectly matched layer as boundary conditions (PML), the optical properties of the proposed design including the birefringence, the effective mode area, nonlinearity, the confinement loss and the chromatic dispersion are investigated in detail. The simulation results demonstrate that the proposed nanowire characterizes an ultra-wideband range of 620 nm for SPSM operation which typically includes all the transmission telecom windows. We have found that the designed SPSM-nanowire exhibits low loss through the slow axis fundamental mode within the wavelengths ranging from 1.28 to 1.9 µm. The confinement loss of the slow axis mode is less than 0.15 dB/km while the fast-axis mode is unguided. Moreover, the dispersion profile can be highly tailored to achieve flat or zero dispersion around the 1.55 µm telecommunication wavelength.

9170-43, Session 8

Generation of ZnSSe and CdZnS nanoparticles by laser ablation in liquids

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Here, we report the synthesis of ZnSSe and CdZnS nanoparticles by laser ablation of the bulk material in different solvents and their characterization by absorption spectroscopy and transmission electron microscopy (TEM). The properties of the resulting particle, which are not stabilized by binding groups other than the solvent, will be discussed.

The laser light used for the ablation was the second harmonic wave (532 nm) of a high frequency Nd:YAG laser.

The pulses were focussed onto a piece of bulk semiconductor, which was held inside a quartz cell with 1 cm pathlength containing 3.5 ml of a solvent. The position of the sample cell with respect to the incident laser beam could be accurately adjusted in three directions by means of micrometer screws. For all experiments a lens with a focal length of 5 cm was used. The laser pulses had a duration of ≈600 ns and pulse energies between ≈5 and 10 mJ. The repetition rate of the laser was generally 50 Hz and the total ablation time per measurement was typically several minutes. The estimated photon fluencies varied between ≈5 and ≈30MWcm-2. Since nonlinear refraction and thermal heating can significantly affect the focussing conditions, the photon fluence at the surface of the semiconductor can vary from solvent to solvent and it depends on the particle yield. The fluence also changes during the ablation process. At the start of an ablation experiment before nanoparticles are formed at a significant number density, the focus is usually tighter, as particle shielding, and refractive and thermal effects are less pronounced. Generally laser ablations were executed in air-saturated solvents which were not stirred during the ablation.

Before each ablation reference spectra of the pure solvents were measured in order to ensure that no traces of impurities remained in the ablation cell. When after the initial laser ablation the particle suspensions were additionally exposed to focussed laser pulses, the colour of the suspensions changed from light grey to almost transparent.

As opposed to the ablation experiment we chose a much higher laser repetition rate for the irradiation experiment since the rate of change of the sample absorption was small. The fact that the laser energy per pulse is smaller at the high repetition rate did not seem to affect the outcome of these experiments. In some samples agglomeration of particles in the form of tiny flakes appearing in the suspension was observed upon prolonged exposure to laser pulses. At first inspection, the change of the spectra could therefore be based on gravitational precipitation of larger particles, which would explain the absorbance decreasing over the entire wavelength range of the spectrum with increasing exposure time.

The semiconductor nanoparticles exhibited different stability in the different solvents. Suspensions of ZnSSe and CdZnS in acetonitrile appeared to be most stable with precipitation times of many weeks. Acetone also stabilized both semiconductor nanoparticles rather well. In alcohols (methanol and also in triethyleneglycol) the particles fell out of suspension more rapidly, typically within days (in the case of ZnSSe in methanol even within a few hours).

We demonstrated that approximately spherical ZnSSe and CdZnS nanoparticles can be produced by laser ablation of the bulk material in solution. The particles are not highly monodispersed with radii of (10±3) nm as shown by TEM. The radii were estimated on basis of a pseudo-potential calculation in the weak and strong confinement regime. The size distribution could be shifted by prolonged laser irradiation of suspensions after the initial ablation; two mechanisms for the size reduction were suggested. The absorption behaviour of nanoparticle suspension is not strongly dependent upon the presence of oxygen during and after ablation. The ablation is not strongly solvent dependent, with the exception of water. A reproducible photoluminescence from laser-ablated ZnSSe and CdZnS particles in suspensions was not observed.

9170-44, Session 8

Deep UV microsphere nanolithography to achieve sub-100 nm feature size

Alireza Bonakdar, Hooman Mohseni, Northwestern Univ. (United States)

Fabrication of nanostructures for bio-sensing and light trapping/extracting applications is typically accompanied by slow production and limited area due to the required sub-micron feature size. In these applications, periodic array of metal/dielectric features can produce important optical resonance responses such as Fano response, chiral response, and negative refractive index. Here, we propose a deep ultra-violet (DUV) photolithography technique that can produce a variety of periodic nanostructure clusters with a sub-100 nm feature size. The method is based on microsphere nanolithography, which focuses DUV field into the so-called photonic nano-jet – a propagative intensive field underneath the sphere. The position of photonic nano-jet can be moved by changing the angle of exposure. The DUV microsphere nanolithography is inherently self-aligned, mask-less and optics-less (the optical element such as lens is not required), which makes this method attractive for low-cost and high-throughput nano-manufacturing schemes, such as roll-to-roll production. Here, we present fabricated arrays of nanoscale complex structures to demonstrate the capabilities of this nanolithography method.

9170-45, Session 8

Optimizing computer control ball polishing of spherical surfaces

Rasool Koosha, Peiman Mosaddegh, Hosein Hashemi, Isfahan Univ. of Technology (Iran, Islamic Republic of)

About half a century ago, computer controlled-polishing (CCP) was represented as a respond to great demand for precision glass manufacturing. Since then, CCP is developed to challenge the difficulties of manufacturing of more complex optical components. Simulation of polishing process and optimization of dwell time are the most prominent key factors of CCP in which numerous papers are published. In this paper, a new model based on discretizing tool path with sub-millimeter distances in length is presented to simulate polishing process. As a result, complex polishing tool path as spiral or epicyclical tool path can be easily and precisely modeled with 50-100 micron accuracy. Converting continuous tool path to discrete points with small steps would improve surface quality in an optimum time and it also reduces fluctuation in tool feed rate. This smooth gradient in feed rate can improve final quality and prevent any damage to polishing machine. Then, a fuzzy algorithm is programmed to optimize the dwell time of polishing process. Considering initial surface error under tool positions and tool influence removal rate, the method calculates optimum dwell time distribution to reduce surface roughness in a short period of time. Both polishing simulation and dwell time fuzzy optimization algorithms are easy to program and could be conducted to operate the CCP on a 3 axis CNC machine. The methodology developed in this study is used for ball polishing of spherical lenses. To establish the authenticity of represented method, a BK7 flat lens with 130 mm in diameter and 320 mm radius in curvature was selected to perform CCP process. The result of initial surface measurement shows 1.114µm of surface roughness for PV (Peak to Valley) and 175 nm for rms (Root Mean Square). The represented method was applied to calculate the optimum dwell time distribution over a spiral tool path with 1 mm in step over. Based on the simulation results, the 3axis CNC machine was programmed to operate polishing process. Based on the final surface measurement, the surface roughness was reduced to 394 nm for PV and 74 nm for RMS. The experimental results show that surface error declined by 64% in PV and 57% in rms which are in good agreement with the modeling.

9170-47, Session PWed

Fabrication of high aspect ratio silicon gratings by interference lithography and potassium hydroxide anisotropic etch technique

Yanchang Zheng, Keqiang Qiu, Univ. of Science and Technology of China (China); Xiaolong Jiang, Qingbo Wang, Lixiang Wu, Lali Bi, Yilin Hong, University of Science and Technology of China (China)

The authors report a new process for the fabrication of 320nm period gratings with ultrahigh aspect ratio on (110) oriented silicon-on-insulator (SOI) wafers. This new fabrication process combines Lloyd-mirror interference lithography with aqueous potassium hydroxide (KOH)

anisotropic etch technique. An alignment method with small error (within ±0.062°) was developed to align grating patterns to the vertical (111) planes of (110) SOI wafers. In addition, a room temperature etch process using 50wt%KOH was chosen to finally get an etch anisotropy of 231. Better etch uniformity was achieved by adding a surfactant to the aqueous KOH to promote the release of hydrogen bubbles. To increase latitude in KOH etching process, evaporation of aluminum under a sloped angle with respect to the grating structures was utilized to obtain a high duty cycle nitride mask. To prevent the collapse of ultrahigh aspect ratio grating structures caused by surface tension, a liquid carbon dioxide supercritical point dryer was used in the drying process. The authors successfully fabricated 320nm period gratings with aspect ratio up to 100 on a 5-um-thick silicon membranes on (110) SOI wafers. This nanofabrication process could also be widely applied in the fabrication of other periods and more complicated silicon gratings.

9170-48, Session PWed

Fabrication and microscopic analysis of sheath-core structured TiO_2 nanofibers

Dong-Gue Kang, Dae-Yoon Kim, Min-Wook Park, Soon-Chun Park, Won-Jin Yoon, Kwang-Un Jeong, Chonbuk National Univ. (Korea, Republic of)

Fabricated nanofibers containing epitaxially grown single crystalline TiO2 nanowires with anatase structure were successfully fabricated by electrospinning method of poly(vinylpyrrolidone) solutions mixed with single crystalline titanium dioxide nanowires and titanium (IV) isopropoxide Ti(OiPr)4 precursor. Utilizing SEM and TEM, morphological examination was conducted. Structure and orientation of the epitaxially grown TiO2 single crystalline nanofibers were also identified by the combined techniques of WAXD and SAED. Improved optoelectronic properties of TiO2 nanofibers were also identified by UV-Vis spectroscopy experiments. This work was mainly supported by Converging Research Center Program (2013K000404), Basic science Research Program (2013R1A1A2007238), Global Ph.D Fellowship Program (2013H1A2A1033907), and BK21 PLUS Program, Korea.

9170-49, Session PWed

Transparent conducting ZnO nanorods for nanoelectrodes as a reverse tunnel junction of GaN light emitting diode applications

Sung Jin An, Kumoh National Institute of Technology (Korea, Republic of)

Homogeneous and heterogeneous semiconductor nanostructures have already been employed for fabricating light emitting devices (LEDs). Despite a remarkable advance in the nanodevice fabrications, the practical use of the nanodevices has still remained out of reach. Meanwhile, well-developed device fabrications in top-down approach have yielded high brightness GaN-based LEDs in a market. Nevertheless, the LED efficiency should be increased for general illumination. Since the internal quantum efficiency is quite high enough, recent efforts on increasing LED efficiency has been focused on enhancing light extraction efficiency by reducing total internal reflection. In addition to the low light extraction efficiency, a highly resistive p-contact layer on nitride semiconductors has been another big obstacle in fabricating high efficiency LEDs. Here we demonstrate that reverse tunnel junction (TJ) LEDs fabricated with a hybrid structure of vertical ZnO nanorod arrays grown on GaN can improve the LED efficiency, size, and structure significantly. The I–V curve of the GaN LEDs with TJ-ZnO NRs exhibits Schottky performance. Also, GaN LEDs with TJ-ZnO NRs demonstrated four times enhanced light output power compared with that of TJ-ZnO thin film, resulting from increased light extraction efficiency. TJ-ZnO NRs offers both high transparent current spreading layer for uniform current injection and easy method for high extraction efficiency. Also, this technique can expand the design flexibility of optoelectronic devices, allowing LEDs without semi-transparent p-contacts and p-GaN etching. More generally, we believe that the simple bottom up heteroepitaxial approach may readily be expanded to fabricate many other heteroepitaxial semiconductor nanorod optoelectrical devices.

9170-50, Session PWed

Nonlinear ultrasound formation in semiconductor structures under its pulse laser irradiation

Mykola Melnichenko, Mykola Isaiev, Oleg V. Lyashenko, National Taras Shevchenko Univ. of Kyiv (Ukraine); Oleksandr I. Vlasenko, V.E. Lashkaryov Institute of Semiconductor Physics (Ukraine); Andrey Kuzmich, National Taras Shevchenko Univ. of Kyiv (Ukraine); Vitaliy P. Veleshchuk, V.E. Lashkaryov Institute of Semiconductor Physics (Ukraine); Roman Burbelo, National Taras Shevchenko Univ. of Kyiv (Ukraine)

Laser irradiation is successfully applied in various areas of modern material research. Such powerful pulse laser irradiation is often used in the processes of nanomaterials fabrication, e.g. when rapid annealing is needed.

Moreover, pulse laser based techniques are essential tools for nanomaterials and nanocomposite structures study. In particularly, laser ultrasound (LU) techniques are perspective for simultaneous investigation of thermal and elastic properties of such materials at different scales. These techniques are based on photoacoustic effect - transformation of absorbed electromagnetic radiation into ultrasonic waves. It should be mentioned that the efficiency of such transformation strongly increased with density of excitation radiation, so the nonlinear phenomena (such as dependence of thermal physical and elastic parameters on temperature) play a crucial role for processes of LU formation.

In this paper the results of theoretical and experimental investigation of ultrasound generated in semiconductors structures under its irradiation by pulse laser irradiation with different wavelengths. It was shown that nonlinear behave of LU amplitude dependence on excitation radiation intensity mainly caused by temperature dependence of thermal conductivity of investigated media. The obtained results could be applied to ensure perfect control for in-situ nanomaterials fabrication processes study.

9170-51, Session PWed

Surface potential and field effect in structures with Ge-nanoclusters grown on Si(100) surface

Yurii Hyrka, Sergiy V. Kondratenko, National Taras Shevchenko Univ. of Kyiv (Ukraine)

The structures consisting of Ge-nanoclusters grown on silicon oxide layer are promising candidates for optoelectronic devices as well as for nonvolatile memory circuits, nanotransistros and solar cells. This is due to their optical and photoconductive properties.

Crystalline germanium nanoclusters (NCs) are grown by a molecular-beam epitaxy technique on chemically oxidized Si(100) surface at 700ºC.

Lateral transport and Kelvin force microscopy measurements have shown that structures with Ge-nanoclusters, grown on oxidized silicon surface characterized by fluctuations of the electrostatic potential caused by spatial distribution of holes trapped by quantum confinement states of Ge-nanoclusters or/and interface traps of Ge-nanoclusters/SiO2 and SiO2/Si interfaces. Field effect on lateral conductivity and surface photovoltage spectra were investigated.

9170-52, Session PWed

Comparison of triangular and squared ITO nano-grating of GaN LEDs

Ashli Behill, Tattiana K. C. Davenport, Xiaomin Jin, California Polytechnic State Univ., San Luis Obispo (United States)

We study nano-scale ITO top transmission gratings to improve light extraction efficiency by optimizing the device parameters. Our study is based on finite difference time domain (FDTD) method to measure light extraction from a device with various grating structures and layer thickness. We simulate our device using a two-dimensional model with top-gratings in a crystal lattice arrangement described by grating cell period (A), grating cell height (d), and grating cell width (w). We also define ITO layer thickness (L), as the layer between the p-type GaN and the ITO surface layers. Simulation models vary in grating period, grating width, and ITO layer thickness. Our simulations monitor the amount of light emitted from the top, bottom, and side of the LED model. These results are used to determine the total light extraction. Our study deals with a LED model with triangular-gratings. We achieve a 165.67% improvement for triangular ITO grating, which has an ITO layer thickness of 230nm, a 230nm grating width and 50 % duty cycle. Our study for square-gratings shows that it also can improve the total light extraction efficiency. Thus far, we have only achieved a 7.16% improvement with an ITO layer thickness of 230nm, a 230nm grating width and 10% duty cycle. We will present our comparison in further detail which will include various ITO layer thicknesses, grating widths and duty cycles.

9170-53, Session PWed

Large strain lead-free ceramics for piezoelectric actuators with nanoscale ceramic-ceramic composite structures

Jae-Shin Lee, Hyun-Young Lee, Jin-Kyu Kang, Univ. of Ulsan (Korea, Republic of); Soon-Jong Jeong, Korea Electrotechnology Research Institute (Korea, Republic of)

Increasing demand for environmentally friendly materials in both electronic and automotive industries promotes extensive studies on lead-free piezoelectric materials in order to replace Pb-based ones that contain over 60 wt% Pb. In this work, we studied the dielectric, ferroelectric, field-induced strain properties of Bi-based lead-free perovskite ceramics with A- or B-site dopants or other ABO3 compounds. Many Bi-based ceramics were found to show large normalized strains in the range of Smax/Emax = 500 – 700 pm/V at RT near ferroelectric-relaxor phase transition region. However, there still remain several challenges to be overcome for field applications; large strain-field hysteresis, high electric-field to trigger large strain, and strain stability in a limited temperature range. In order to overcome such barriers, we attempted to prepare ceramic-ceramic composites by embedding ferroelectric particles in a relaxor matrix, resulting in lowering the triggering field even though the maximum strain was almost unchanged. The ceramic-ceramic composites are believed to enlighten a new road to large strain lead-free alternatives of Pb-based actuator materials.

9170-54, Session PWed

Lightfast optical current in dielectric by plasmonically induced local field

Seungchul Kim, Pohang Univ. of Science and Technology (Korea, Republic of) and Max Planck Ctr. for Attosecond Science (Korea, Republic of); Ojoon Kwon, Pohang Univ. of Science and Technology (Korea, Republic of)

Recently, ultrafast strong field induced optical current in SiO2 dielectric medium has demonstrated. By inducing laser intensity more than 10^13 W•cm-2, the optical current was generated in a dielectric gap without any DC bias. This phenomena is affected by the magnitude electric field of incident laser field and the generated current follows the speed of optical frequency enabling lightfast electronics in the future. In this study, we especially applied nanoplasmonic field to trigger and control current flow in a nanometer spatial resolution. Nanoplasmonic field enables to manipulate light field in nanoscale domain. By using nanoplasmonic field, optically induced current flow can be selectively controlled by characteristic of nanoplasmonic nanostructure.

For that, saw tooth like 2D nano Au pattern was numerically and experimentally investigated to boost up the intensity of incident 3.5 fs few cycle laser with minimum field distortion and broadening. The intensity enhancement factor of plasmonic field at the saw tooth tip was ~40 enabling Wannier–Stark effect at incidence intensity level of only 10^11W•cm-2. This will be useful for developing practical lightfast optical electronics in the future.

9170-55, Session PWed

Preparation of Bi-based lead-free ceramic multilayer actuators

Jae-Shin Lee, Jin-Kyu Kang, Young Hwan Hong, Dae-Jun Heo, Dong-Wook Lee, Univ. of Ulsan (Korea, Republic of)

Piezoelectric materials that can interchangeably convert mechanical to electrical energy are widely used as sensors and actuators for electronic, automotive, and medical applications. Increasing demand for environmentally friendly materials in both electronic and automotive industries promotes extensive studies on lead-free piezoelectric materials in order to replace Pb-based ones that contain over 60 wt% Pb.

In this work, Pb-free multilayer ceramic actuators (MLAs) including Nb-doped Bi1/2(Na,K)1/2TiO3 (BNKT:Nb) ceramic layers with electrically conducting AgPd-ABO3 thick films were prepared using tape-casting and screen-printing. The co-firing induced defects in the MLAs were analyzed by examining co-firing induced deflections and microcracks as a function of sintering temperature as well as the composition of the inner electrode. It was found that co-firing induced deflections were significantly relieved by employing AgPd-ABO3 composite layers as inner electrodes instead of pure AgPd via reducing thermal mismatch between the electromechanical and electrode layers. We have successfully fabricated lead-free electrostrictive multilayer actuators with normalized strain Smax/Emax of 350 pm/V, which seems very promising for lead-free actuator applications.

9170-56, Session PWed

Graphene based multi-cavity terahertz absorbers

Jeong Min Woo, Hyunwoong Kim, Sungbae J. Lee, Jae-Hyung Jang, Gwangju Institute of Science and Technology (Korea, Republic of)

Terahertz (THz) frequency band has promising applications in the areas of security imaging, cancer diagnosis, and bio-sensors because THz wave has non-ionizing bio-innocuous property, transparent characteristics against cardboard or textile, and highly selective absorption spectral lines that can be used as “fingerprint” of various bio-materials.

For the construction of more application agile THz systems, devices, which emit, detect, absorb, and control THz waves efficiently, are required. THz absorbers are also interesting to selectively or totally reject background THz radiation in THz sensor systems.

In this study, graphene layers were utilized as thin resistive films to construct Salisbury screen absorbers and Jaumann absorbers in THz frequency range. The sheet resistance of graphene layer can be easily controlled by chemical modification of graphene surface to achieve optimum absorbance in both types of the absorbers. Salisbury screen

consists of a graphene layer, dielectric spacer layer, and backside reflector. The fabricated Salisbury screen based absorber exhibited multiband spectral responses with periodic absorption frequencies. Jaumann absorber consisting of periodically arranged multiple dielectric spacer layers sandwiched by multiple graphene layers and backside reflector provides wider bandwidth compared with Salisbury screen absorbers.

A Salisbury screen based absorber with chemically doped graphene layer having sheet resistance of 689 □/Ω exhibited absorbance values of 0.95 and 0.97 at 0.5 and 1.5 THz, respectively, and 3-dB bandwidth of 0.6 THz. Jaumann absorbers with double and triple stacked structures exhibited absorbance values of 0.72 and 0.92 at 0.5 THz, and much wider 3-dB bandwidths of 0.84 THz and 0.86 THz, respectively.

9170-57, Session PWed

Formation of sub-wavelength pitch regular structures employing a motorized multiple exposure Lloyd's mirror holographic lithography setup

Dainius Virganavicius, Linas Simatonis, Ausrine Jurkeviciute, Tomas Tamulevicius, Sigitas Tamulevicius, Kaunas Univ. of Technology (Lithuania)

Today technology is moving towards a direction of scaling down things to ever smaller dimensions. The trend since started by IC industry is expanding now into other areas, e.g. photonics, MEMS, microfluidics, sensors, etc. For that reason, there is an immense demand for techniques capable of producing nanoscale structures. Holographic lithography (HL) is emerging as a very promising, powerful and cost effective technique for surface patterning, among them. The biggest limitation of HL is that only periodic patterns can be produced. Despite this drawback, HL has been shown to be applicable for structuring photonic crystals, nanowires, porous membranes, magnetic dots, etc.

In this work 1D and 2D periodic nano structures in thin positive and negative tone photoresist, spin coated on float glass and crystalline silicon substrates were fabricated employing advanced, fully automated Lloyd mirror HL setup. The exposures were performed employing 15 mW power and 375 nm wavelength solid state laser with a coherence length extending over few meters. The laser beam was expanded employing microscope objective with 99 % transmission at the laser wavelength. 2D patterns were obtained applying sequential exposures with the sample rotation in between. Regular structures with different point lattice symmetries with half pitches reaching 100 nm were fabricated and investigated employing scanning electron and atomic force microscopes. The produced regular structures were used in the technology of refractive index sensors based on diffractive leaky wave mode as well as templates for capillary assisted particle deposition.

9170-59, Session PWed

InP nanowires with axial/radial junctions for applications as light emitting diodes and photodetectors

Ali Nowzari, Lund Univ. (Sweden); Vishal Jain, Lund Univ. (Sweden) and Halmstad Univ. (Sweden); Magnus Heurlin, Kristian Storm, Magnus T. Borgstrôm, Lund Univ. (Sweden); Håkan Pettersson, Lund Univ. (Sweden) and Halmstad Univ. (Sweden); Lars Samuelson, Lund Univ. (Sweden)

Semiconductor nanowires with their sub-wavelength dimensions have opened a new era in semiconductor optics. Today nanowires can be fabricated with different compositions and structures, suitable for applications as light sources, detectors, light propagation media, solar cells and other optical devices. The nanometric dimensions of nanowires allows heteroepitaxy of III-V materials on Si, a major trend in realizing optoelectronic devices. InP nanowire-based Light emitting diodes (LEDs) and Photodetectors(PDs), monolithically integrated on Si, and operating at suitable wavelengths, can potentially be configured as transmitters/receivers for on-chip optical interconnects. In this work vertical arrays of InP nanowires, grown by MOCVD method on Nanoimprint Lithography (NIL) patterns are used to fabricate LEDs and PDs. p-i-n Junctions are formed axially throughout the length of the Nanowires as well as radially in the Core-MultiShell(CMS) configuration. Infrared LEDs has been fabricated and tested for electroluminescence as well as Infrared PDs tested for light response.

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9171-1, Session 1

Natural and nature-inspired semiconductors for biocompatible electronics *(Keynote Presentation)*

Eric D. Glowacki, Niyazi Serdar Sariciftci, Johannes Kepler Univ. Linz (Austria)

Many natural chromophores have recently emerged as suitable semiconducting materials for (opto)electronic applications. The motivation for exploring such molecules is the realization of biodegradable and biocompatible electronics fabricated from cheap and nontoxic materials. We find that natural pigment-forming dye molecules, such as those from the indigo family, form highly-ordered thin films with excellent ?-stacking. Using such films, we have demonstrated field-effect transistors (FETs) and complementary-like circuit elements utilizing exclusively natural materials operating at the state-of-the-art level with respect to mobility and operational stability in ambient conditions. These dyes show air-stable ambipolar charge transport with balanced hole and electron mobilities in the range of 1x10-2 – 2 cm2/Vs. Hydrogen-bonding causes strong intermolecular electronic coupling, resulting in optical properties dominated by excimeric and charge-transfer effects. A very important property is that these molecules form high crystal lattice energy solids with exceptional operational, thermal, and chemical stability. FETs with indigos can be operated without any passivation in highly-demanding aqueous environments, within a pH range from 3-11 and with a variety of different ions. We report on the results of stressing tests in such underwater environments. The –NH and =O functional groups lend themselves to easy functionalizing, which we have exploited to two ends: 1) creation of stable colloidal nanocrystals with controllable morphology and optical properties, and 2) biofunctionalization. We discuss also preliminary experiments concerning field-effect transistor biodetectors based on these materials. Hydrogen-bonded natural and nature-inspired materials are an interesting and previously unexplored class of organic semiconductors with inherent potential for biointegrated applications.

9171-2, Session 1

Electrical conductivity and impedance behaviour of hydrogel materials *(Invited Paper)*

Holly Warren, Marc in het Panhuis, Univ. of Wollongong (Australia)

No Abstract Available

9171-3, Session 1

Effective bioimaging by using organic chromophores and nanoparticles *(Invited Paper)*

Kwang-Sup Lee, Hannam Univ. (Korea, Republic of)

No Abstract Available

9171-4, Session 1

Organic semiconductor biophotonics *(Invited Paper)*

Ashu K. Bansal, Shuoben Hou, Olena Kulyk, Andrew McNeill, Eric Bowman, Univ. of St. Andrews (United Kingdom); James Ferguson, Ninewells Hospital and Medical School (United Kingdom); Ifor D. W. Samuel, Univ. of St. Andrews (United Kingdom)

There is a growing trend in medicine towards compact devices for monitoring and treatment. Such devices would ideally be flexible and wearable , thereby enabling ambulatory monitoring and treatment in which the patient can move around. Organic semiconductors have attractive properties for realizing this vision as they enable thin and flexible devices to be made. In this talk I will show three examples of such applications. The first is the development of a wearable light sources for skin cancer treatment. The second is a sensor using polymer LEDs and photodiodes to measure changes in tissue oxygenation. The third application is a muscle contraction sensor in which anisotropic scattering of light from a polymer LED is detected by polymer photodiodes, giving an optoelectronic device that could control a prosthetic limb. These results provide interesting directions for polymer optoelectronics, and the possibility of measuring a range of important biomedical processes.

9171-5, Session 2

The synthesis and bio/nano applications of DNA brushes *(Invited Paper)*

Kuniharu Ijiro, Hokkaido Univ. (Japan)

Polymer brushes are polymers in which individual polymer chains stand side by side on a surface, causing the chains to stick out like bristles on a brush. A DNA brush is a kind of polymer brushes. We newly prepared DNA brushes through the immobilization of biotinylated oligo-DNA on the streptavidin substrate and polymerization by DNA polymerase (Klenow Fragment exo-) as a surface initiated polymerization. To confirm the appearance and feature of the DNA brush, we determined the length and density of the grafted DNA and evaluated surface physical property. The DNA brushes were applied for the substrates of cell culture, functional interfaces and advanced lithography technology.

9171-6, Session 2

Deoxyribonucleic acid-Ag nanoparticles for EMI Shielding: the effect of nanoparticle size and shape on the shielding effectiveness

Fahima Ouchen, Perry P. Yaney, James G. Grote, Air Force Research Lab. (United States)

No Abstract Available

9171-7, Session 2

Metal array structures on the stimuli-responsive gel *(Invited Paper)*

Hideyuki Mitomo, Naonobu Shimamoto, Kenta Horie, Yasutaka Matsuo, Kenichi Niikura, Kuniharu Ijiro, Hokkaido Univ. (Japan)

Now technologies to fabricate nano-structures have been established well. And hydrogels are well known as the stimuli responsive materials. A large volume change can be induced by absorbing or exuding water, namely swelling or deswelling, on the hydrogel. In this work, we have developed the fabrication method of nano- or micro-patterned metal thin film on hydro-gels. We prepared gold (Au) thin film pattern on Si substrate by using top-down or bottom-up fabrication method. Molds for the gels were made up from the Si substrate with Au thin film pattern, transparent slide glass and silicone rubber spacer. We poured the monomer solution

into the mold and carried out the polymerization by UV irradiation for several hours. After that, hydro-gels with thin film patterns were released from the mold. Au thin film patterns were transferred on the PAA gel due to their interaction and the gel showed structural colors depending on the dot spacings or the plasmon absorption. These structural colors or plasmon absorption were changed when the gel was immersed in various NaCl solutions because the distance between each Au dot had been changed by swelling and shrinking of the hydrogel. This shows that we created a new type of tunable photonic devices based on soft and wet matters.

9171-8, Session 2

A thylakoid layer-by-layer assembly for stable cell-free photosynthesis devices

Bong Sup Shim, Yuran Shon, Hongsup Hwang, Hyun Kim, Inha Univ. (Korea, Republic of)

Spinach chloroplast thylakoids, on which complete sets of photosynthetic membrane proteins are preserved and which behaved as nanoparticles, were densely organized by molecularly controlled layer-by-layer (LBL) assembly. The resulting nanostructured composite films showed photoelectrochemical activities with thylakoids whose stabilities were much improved on the LBL multilayers compared to one on a randomly structured film or in solution. The thylakoids LBL films could generate photochemical electrons continuously with the 2,6-dichlorophenolindophenol (DCPIP) mediated photosynthetic energy conversion cycle for more than a week. The PC12 neural cells were also proliferated and differentiated on this nanostructured photosynthesis film. Because the photofunctional groups of the films originated from a purely biotic system, the reported thylakoid LBL film have biocompatibility, biosafety, and biodegradability, essential qualities of eco-friendly electronic applications, such as in disposable electronics and implantable meditronics, as well as cell-free fuel production.

9171-9, Session 2

Electrochemical properties of some DNA based materials *(Invited Paper)*

Ileana Rau, Gratiela Tihan, Mihaela Mîndroiu, Roxana Zgarian, François Kajzar, Univ. Politehnica of Bucharest (Romania); Lucas Marinho Nobrega de Assis, F. Sentanin, Agnieszka Pawlicka, Univ. de São Paulo (Brazil)

No Abstract Available

9171-10, Session 3

Optics and nanophotonics enabled by genetically-engineered short peptides *(Keynote Presentation)*

Mehmet Sarikaya, Univ. of Washington (United States)

No Abstract Available

9171-11, Session 3

Investigation of a DNA nucleobase as a gate dielectric for potential application in a graphene-based field effect transistor

Adrienne Williams, Fahima Ouchen, Steve S. N. Kim, Yen H. Ngo, Air Force Research Lab. (United States); Said Elhamri, Univ. of Dayton (United States); Shin Mou, Air Force Research Lab. (United States); Henry D. Young, Wright State Univ. (United States); Rajesh R. Naik, James G. Grote, Air Force Research Lab. (United States)

In this study, we investigated use of various substrates-silicon carbide, glass, kapton, photo print paper, polydimethlysiloxane, and willow glass in the transfer of graphene. Four monolayers of graphene were transferred onto these substrates in which bulk charge carrier mobilities were determined. Guanine was physically vapor deposited at ~60 nm onto the substrates that showed consistency in the transport measurements. Room temperature transport measurements were obtained with the Guanine on these substrates for 3 and 6 days. For the first time, we observed room temperature stability measurements with Guanine as the dielectric material physically vapor deposited onto transferred graphene. Specifically, these transport measurements were significantly more stable with the Guanine, but with a significant decrease in bulk carrier mobility with PMMA.

9171-12, Session 3

Nonlinear optical properties of chromophore functionalized DNA-surfactant complexes *(Invited Paper)*

François Kajzar, Ana-Maria Manea, Univ. Politehnica of Bucharest (Romania); Valentin I. Vlad, National Institute for Lasers, Plasma and Radiation Physics (Romania); Adrian Petris, National Institute for Laser, Plasma and Radiation Physics, Department of Lasers, (Romania); Tatiana Bazaru Rujoiu, National Institute for Lasers, Plasma and Radiation Physics (Romania); Alexandrina Tane, Ileana Rau, Univ. Politehnica of Bucharest (Romania)

Recent results on DNA functionalization, thin film processing and characterization of their nonlinear optical (NLO) by optical third-harmonic generation will be reported and discussed. In particular the results concerning influence on the matrix on chromophore electronic structure and resulting NLO response will be presented. The results of photothermal and chemical stability of thin films studies will be also reviewed.

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9171-13, Session 3

Hyper Rayleigh scattering of biomolecules: the case of thymine and adenine *(Invited Paper)*

Anthony Maurice, Univ. Claude Bernard Lyon 1 (France); Franck Bertorelle, Univ de Claude Bernard Lyon I (France); Emmanuel Benichou, Pierre-François Brevet, Univ. Claude Bernard Lyon 1 (France)

The measurement of the hyperpolarizability of biomolecules is essential to develop a quantitative analysis of the Second Harmonic Generation (SHG) from biological tissue. Beyond this measurement, generally hampered by the weakness of the hyperpolarizability measured, the underlying question of the development of models to rationalize the hyperpolarizability of peptides and proteins is addressed. We discuss this point of view for aromatic and non aromatic amino acids.

9171-16, Session 3

Natural materials for nano bio systems *(Invited Paper)*

James G. Grote, Air Force Research Lab. (United States)

No Abstract Available

9171-14, Session 4

Light amplification and lasing from dyes doped in DNA-complex thin films prepared by soaking method *(Invited Paper)*

Yutaka Kawabe, Takemasa Suzuki, You Iisaka, Chitose Institute of Science and Technology (Japan)

An alternative fabrication method for dye-doped DNA-surfactant complex films was developed and amplified spontaneous emission (ASE) and lasing under low energy optical pumping were demonstrated.

In this new preparation technique, thin DNA-cethyltrimethylammonium (CTMA) complex films were made by a conventional spin coating method, and were applied to the process of staining with a hemicyanine dye by soaking films in acetone solution of the dye for one day. Molar ratio of the dye to DNA for the final products was estimated to be 1/5, the value was much higher than those achieved via usual mixing method. ASE threshold under the pumping of a pulsed frequency-doubled YAG laser was about 0.3 mJ/cm2. Laser emission was also available under the pumping with two interfering beams forming a dynamic grating of gain coefficient. Durability test indicated that 70% of their initial performance was maintained after 1 hour of continuous optical pumping.

This technique was applied to water soluble dyes because the DNA complex was insoluble to water as well as acetone. We employed anionic Eosin Y dye, succeeding in sample formation and ASE emission. Different types of surfactants were also complexed with DNA, showing dependence of emission peak wavelength.

These results give a clue about the structure or interaction modes between DNA and surfactants, suggesting strongly that dye molecules are not intercalated into nor bound to DNA double strand directly, but are incorporated in the DNA system via ion-exchange process or aggregating with cationic surfactants.

9171-15, Session 4

Random lasing in dye doped bio-organic based systems: experimental and stochastic approach *(Invited Paper)*

Antoni C. Mitus, Grzegorz Pawlik, Jaroslaw Mysliwiec, Lech Sznitko, Konrad Cyprych, Adam Szukalski, Andrzej Miniewicz, Wroclaw Univ. of Technology (Poland); François Kajzar, Ileana Rau, Univ. Politehnica of Bucharest (Romania)

We present results of detailed experimental studies on random lasing phenomenon achieved in biopolymeric matrices based on modified deoxyribonucleic acid loaded with different luminescent dyes. The random lasing originates due to the light scattering induced by formation of microcrystals or clusters in the bulk of biosystem. The mechanism of diffusive transport of light, its amplification and randomization in biopolymeric matrices is studied theoretically in terms of non-standard diffusion approach, including sub/super diffusion, continuous time random walk and Levy flights.

9171-17, Session 4

BioTFT memory with DNA gate dielectric and its thermal property *(Invited Paper)*

Norihisa Kobayashi, Kazuki Nakamura, Chiba Univ. (Japan); Sei Uemura, Toshihide Kamata, National Institute of Advanced Industrial Science and Technology (Japan)

No Abstract Available

9171-32, Session 4

Summary report on AFRL studies of the optical and electrical properties of biopolymers using salmon DNA *(Invited Paper)*

Perry P. Yaney, Univ. of Dayton (United States); Fahima Ouchen, James G. Grote, Air Force Research Lab. (United States)

No Abstract Available

9171-18, Session 5

DNA film on the surface and inside the capillary for optoelectronic and photonic applications *(Invited Paper)*

Kyunghwan K. Oh, Seongil Im, Yeonjin Yi, Jae Hoon Kim, Yonsei Univ. (Korea, Republic of); Juhiuk Son, The Univ. of Seoul (Korea, Republic of); Sung Ha Park, Sungkyunkwan Univ. (Korea, Republic of); Dong Ki Yoon, Yoon Sung Nam, KAIST (Korea, Republic of); Woohyun Jung, Bjorn Paulson, Inchul Shin, Ji-Hyung Hwang, Yonsei Univ. (Korea, Republic of)

DNA has been recently modified to be dissolved in organic solvents, which enabled thin film fabrication. DNA thin films have initiated a new area of research DNA optoelectronics, to investigate optoelectronic properties of the most abundant organic substance. In our research group formed by Yonsei, SKKU, KAIST, and KIST have focused on fabrication of DNA material from the nanoscopic to microscopic scale. We present optical properties of DNA solid, liquid, from UV to tera Hertz range. Transmission, refractive index, and absorption were measured. Waveguides fabrication based on various DNA films are also reported. In terms of electronic transport, we also present the unique capability of Guanine base in thin film transistors. Linear and nonlinear properties of DNA films, solutions were also characterized.

9171-19, Session 5

Photobleaching for DNA-based photonic devices *(Invited Paper)*

Bjorn Paulson, Inchul Shin, Reza Khazaeinezhad, Sahar Hosseinzadeh Kassani, Woohyun Jung, Kyunghwan K. Oh, Yonsei Univ. (Korea, Republic of)

One of the major unsolved challenges in the field of DNA-based photonics involves the scarcity of methods for the controlled, repeatable, and efficient fabrication of all-DNA biopolymer waveguides. We investigate the efficacy of photobleaching bulk DNA and DNA-CTMA thin films to cause permanent refractive index change, with the goal of forming waveguides and more complex structures. Both continuous and pulsed lasers in the UV and visible have been tested for bleaching effect on bulk DNA films formed by drop casting and on DNA-CTMA films formed by a mix of drop casting and spin coating. Due to concerns about

the accuracy of ellipsometric data on DNA thin films, bleaching efficacy is being tested by attempted device fabrication, as well as by ellipsometry. At present an aluminum mask is used to physically shadow a region of the thin film into a patterned channel waveguide structure. Waveguiding by the channel waveguides is tested by coupling light from a fiber taper into the edge of the thin film, and looking for a diffraction pattern in the far-field light emitted at the opposing edge. Additional work may involve the use of lanthanide ion- or transition metal ion-doped DNA films.

9171-20, Session 5

Modified polymer thin film device architecture for increased energy density

Donna M. Joyce, Fahima Ouchen, James G. Grote, Air Force Research Lab. (United States)

No Abstract Available

9171-21, Session 6

Photo Seebeck effect of conjugated polymers *(Invited Paper)*

Eunkyoung Kim, Yonsei Univ. (Korea, Republic of)

No Abstract Available

9171-22, Session 6

Micro and nanostructuration of polymer materials and applications *(Invited Paper)*

Thi Thanh Ngan Nguyen, Mai Hoang Luong, Mai Trang Do, Duy Manh Kieu, Qinggele Li, Dam Thuy Trang Nguyen, Quang Cong Tong, Isabelle Ledoux-Rak, Ngoc Diep Lai, Ecole Normale Supérieure de Cachan (France)

Polymer materials offer unique opportunities in nanophotonics and nanobiosystem since both top-down and bottom-up strategies can be pursued and combined towards the nanoscale. Besides, polymer materials can be, with simple methods, functionalized with nonlinear optical or fluorescent materials (organic, inorganic, or metal). The ensemble can be optically structured in a flexible way to obtain a polymer-based photonic nanostructure ("host") containing active materials ("guest"), which may provide an enhancement of the guest optical response, leading to attractive applications. For example, the fabricated polymer structures may find easily applications in the domain of the detection and analysis of chemical or biological species for environmental monitoring, protection against hazardous agents, and for various issues related to health. In this talk, I will explain two important fabrication techniques, namely interference and one-photon absorption direct laser writing, which present different advantages and allow both to obtain desired micro and nanometric 2D and 3D structures. I also discuss about some potential applications of these polymer-based structures, for example, for laser, nonlinear optics, and plasmonics.

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9171-23, Session 6

Diatom frustule photonic crystal geometric and optical characterization

Jonathan Mishler, Phillip Blake, Andrew J. Alverson, Donald K. Roper, Joseph B. Herzog, Univ. of Arkansas (United States)

Diatom algae are single-celled, photosynthetic organisms, with an exoskeleton called a frustule; a periodically patterned structure made of silica. Over the last decade, diatom frustules have been researched as possible candidates for photonic crystals. A MATLAB program characterizing the periodic structures of diatom frustules from an SEM image was developed to determine how their periodic structures determine their optical properties. This program outputs the physical distance of each pore edge to the pore centroid as a function of angle for each pore. SEM images from a variety of centric diatoms were input into the program, and their pore geometries were characterized. Correlations between their respective pore geometries and optical properties were then established, giving insight as to how artificially manufactured photonic crystals should be designed for specific optical properties. Furthermore, numerical methods were used to computationally model the optical properties of diatom frustules. By artificially varying the pore geometry of the frustules, new optical nanostructures were designed for use as biomimetic plasmonic crystals.

9171-24, Session 6

Novel pH-sensitive probes with a ratiometric detection for intracellular pH

Ipuy Martin, Ecole Normale Supérieure de Lyon (France); Cyrielle Billon, Univ. de Lyon (France); Guillaume Micouin, Ecole Normale Supérieure de Lyon (France); Jacques Samarut, Univ. de Lyon (France); Chantal Andraud, Ecole Normale Supérieure de Lyon (France); Bretonniere Yann, Ecole Normale Supérieure de Lyon (France)

Phenolic compounds are amongst the most important class of dyes. The main characteristic property of phenols is the acidity of the OH group. This unique property has been intensively exploited in the design of fluorescent indicator for intracellular pH.

We will present here the design, the synthesis and the study of the physical and optical properties of a new series of simple push-pull dipolar phenol derivatives containing the 2-dicyanomethylene-3-cyano-4,5,5-trimethyl-2,5-dihydrofurane (DCDHF) ring. Spectrophotometric procedures enabled determining the pKa values by a non linear regression of the sigmoidal response of absorption value vs pH. The fluorescence properties of all compounds were also studied in water and the most promising ones were incubated in cells to monitor intracellular pH variations.

This large family can be obtained in a simple synthesis through a Knoevenagel condensation performed by controlled microwave irradiation. The pKa values vary from 4.2 to 8.9, which span the intracellular pH range. As expected, installation of electro-withdrawing group ortho to the hydroxy group induces a decrease of the pKa value. The different dyes present a ratiometric fluorescence with maxima around 550 nm (phenol) and 620 nm (phenolate). The overall brillance of these objects reach 500 to 4000 L.mol-1.cm-1.

Moreover, study of the variation of fluorescence or fluorescence intensity ratios as a function of pH show a good response around physiological pH. Those fluorophores also present a very fast cellular uptake and are easily visualized by fluorescence microscopy making them very good candidates for intracellular pH probes.

9171-33, Session 6

Non-volatile organic memory with extreme flexibility *(Invited Paper)*

Cheolmin Park, Yonsei Univ. (Korea, Republic of)

No Abstract Available

9171-25, Session PWed

Hyper Rayleigh and hyper Raman from neat water

Anthony Maurice, Univ. Claude Bernard Lyon 1 (France); Qianli Ma, CEA, Direction de l'Energie Nucléaire, Département de Radiochimie des Procédés (France); Emmanuel Benichou, Univ. Claude Bernard Lyon 1 (France); Fabrice Canto, Laurent Couston, CEA, Direction de l'Energie Nucléaire, Département de Radiochimie des Procédés (France); Pierre-François Brevet, Univ. Claude Bernard Lyon 1 (France)

The observation of hyper Rayleigh Scattering from aqueous solutions is in effect an adequate configuration to observe hyper Raman Scattering too. Even though neat water is not a strong Raman scattering medium, bands located near 670 cm-1 and 3450 cm-1 for instance are easily observed. In the past, two geometrical configurations have been used to observe both hyper Rayleigh and hyper Raman Scattering, namely right angle and backward collection. We re-investigate here this problem and discuss the effect of the collection configuration on the measured intensities.

9171-26, Session PWed

Energy transfer within sub-nanoscale arrangements of DNA-templated chromophores and lipid-DNA nanocomplexes

Ho Yeon Son, KAIST (Korea, Republic of)

Light-harvesting antenna in natural photosystem are precisely designed through self-assembly of functional molecules with large protein complexes in a thylakoid lipid bilayer. The exquisite antenna in biological systems absorb the light, transfer the resulting excitation energy in a long distance, and finally direct it to a reaction center for charge separation and catalysis. However, sub-nanometer arrangement of chromophores into a stable macro-scale structure for a long-range, directed transfer of excitation energy has not yet been achieved in artificial light-harvesting systems. Here we introduce a multi-scale assembly approach of chromophores for a long-range Förster-type resonance energy transfer (FRET) by arranging chromophores on a nanoscale using DNA templates and incorporating the DNA-templated chromophores into larger lipid structures. Single strand DNA molecules containing a terminal residue linked with three different chromophores (JOE, TAMRA, and TexasRed) are hybridized with their complementary matrix DNA strand. The FRET efficiencies and antenna effects of the single and double-step energy transfers dramatically increase by the incorporation of DNA-templated chromophores into DNA-lipid complexes, which enable the secondary assembly of DNA between the inter-lipid spaces of multi-lamellar lipid structures. We expect that the supramolecular alignment of DNA-templated chromophores, which has never been explored previously, can be a very promising route toward directed, long-range light-harvesting for a wide range of applications in photocatalysis, sensing, and optoelectronics.

9171-27, Session PWed

Viral-templated nanocrystalline Pd nanowires for chemiresistive hydrogen (H2) sensors

Chung Hee Moon, Yiran Yan, Miluo Zhang, Nosang V. Myung, Elaine D. Haberer, Univ. of California, Riverside (United States)

A palladium (Pd) nanowire-based hydrogen (H2) sensor has been fabricated with a novel viral-templated assembly route. H2 is a promising zero-emission fuel that has the potential to replace fossil fuels in many applications. It is odorless and non-toxic, yet extremely flammable above 4% in air due to its low ignition energy. In development of H2 fuel cells, a H2 sensor that can rapidly detect low concentrations of H2 gas is required to ensure safety. Palladium has been reported as a suitable material for H2 sensing due to its catalytic property and its increasing electrical resistance when reacted with H2 to form alpha-palladium hydride (?-PdHx). In this report, we have fabricated a viral-templated Pd nanowire-based sensor for sensitive, room temperature detection of H2. A filamentous M13 bacteriophage has been used as the viral-template for assembly of Pd nanowires at ambient conditions. The nanowires provide large surface area for effective and rapid H2 gas-Pd surface interaction, which in return, enhances sensor performance. Seed-mediated synthesis of Pd nanowires was performed on a genetically-modified gold-binding virus decorated with gold nanoparticles. The morphology and nanowire distribution of the device were observed under the scanning electron microscope and transmission electron microscope. The electrical resistances of the devices were controlled by modifying material deposition on the viral-template. Sensor performance was analyzed by exposing the devices to H2 concentrations from 100 to 2000 ppm. The M13 bacteriophage template enabled facile, ambient condition fabrication of Pd nanowires for rapid, sensitive H2 sensing at room temperature.

9171-28, Session PWed

Physicochemical characterization of silver nanoparticles synthesize using Aloe Vera (Aloe Barbadensis)

Abiola J. Kuponiyi, Lamin Kassama, Tatiana V. Kukhtareva, Alabama A&M Univ. (United States)

Production of silver nanoparticles (AgNPs) using different biological methods is gaining recognition due to their multiple applications. Although, several physical and chemical methods have been used for the synthesis and stabilizing of AgNPs, yet, a green chemistry method is preferable because it is cost effective and environmentally friendly. The synthesis was done using Aloe Vera (AV) extract because it has chemical compounds such as "Antrokinon" that are known for its antibacterial, antivirus and anticancer properties. We hypothesize that AV extract can produce a stable nanoparticles within the 100 nm range and be biologically active. The biological compounds were extracted from AV skin with water and ethanol which was used as the reduction agent for the synthesis of nanoparticles. The biological extract and AgNO3 were blended and heated to synthesize AgNPs. The reaction process was monitored using UV-Visible spectroscopy. Fourier Transfer Infrared spectroscopy (FTIR) was used for the characterization of biological compounds and their substituent groups before and after the reaction process. Dynamic Light scattering (DLS) method was used to characterize particle size of AgNPs and their bio-molecular stability. Results showed that biological compounds such as aliphatic amines, alkenes (=C-H), alkanes (C-H), alcohol (O-H) and unsaturated esters(C-O) which has an average particle size of 109 and 215.8 nm and polydispersity index of 0.451 and 0.375 for ethanol and water extract, respectively. The results suggested that ethanol derived AgNPs contained higher yield of organic compounds, thus has better solubility power than water. Ag NPs can be used to control salmonella in poultry industry.

9171-29, Session PWed

Toward a chemiresistive ammonia (NH_3) gas sensor based on viral-templated gold nanoparticles embedded in polypyrrole nanowires

Yiran Yan, Univ. of California, Riverside (United States); MILUO ZHANG, University of California (United States); Heng Chia Su, Nosang V. Myung, Elaine D. Haberer, Univ. of California, Riverside (United States)

Ammonia (NH3) is used in many industries such as agriculture, fermentation, and refrigeration. Yet, it is a highly toxic and corrosive gas. For this reason, sensitive, selective and fast NH3 detection is important. Polypyrrole (Ppy), a p-type semiconducting polymer, exhibits a reversible, yet sluggish increase in resistance when exposed to NH3 gas due to slow analyte diffusion within bulk material. The large surface-to-volume ratio of nanostructured Ppy can overcome these kinetic limitations by facilitating analyte diffusion, thus enabling rapid sensing response and recovery. In this work, a M13 viral template was utilized to assemble chemiresistive Ppy-based, nanowire NH3 gas sensors. The high aspect ratio of this filamentous virus, which is approximately 6-7 in diameter and 880 nm in length, assisted nanowire formation. A genetically-modified M13 bacteriophage which displayed an 8-mer gold-binding peptide along its length was used to direct the assembly of linear chains of gold nanoparticles on which Ppy was subsequently electrodeposited. To fabricate NH3 gas sensors, gold nanoparticle-embedded Ppy nanowires were assembled on Si/SiO2 substrate pre-patterned with gold electrodes. The morphology, surface density, and connectivity of the nanowires between the electrodes were examined by scanning electron microscopy. The viral template surface density and Ppy electrodeposition time were used to control electrical resistance of the sensor. Finally, sensor performance was evaluated for NH3 gas concentrations from 40-300 ppm, as a function of resistance. In conclusion, we have developed a unique method of assembly for nanowire Ppy-based NH3 sensors.

9171-30, Session PWed

Morphology manipulation of M13 bacteriophage template for nanostructure assembly

Tam-Triet Ngo-Duc, Mohammed S. Zaman, Univ. of California, Riverside (United States); Chung-Hee Moon, University of California, Riverside (United States); Elaine D. Haberer, Univ. of California, Riverside (United States)

With the rapid advance of nanotechnology, the demand for versatile techniques capable of arranging molecular and nanoscale objects with nanometer precision has grown. Biomolecules have nanoscale characteristic lengths and molecular recognition capabilities which are extremely valuable in designing and building nanomaterials. Specifically, viral capsids have proven particularly useful for in vitro assembly in which hierarchical structure is critical. Through genetic engineering, the properties and functionalities of viral proteins can be controlled, creating a programmable scaffold for inorganic material assembly and/or synthesis. Yet, a significant disadvantage exists for this approach. The overall structure or architecture of a specific virus cannot be drastically modified. A different virus must be engineered and characterized for each geometry-specialized (i.e. sphere, rod, filament) application. The M13 filamentous phage, which can be converted from its initial wire-like form to a rod to a spheroid through simple exposure to chloroform, poses a unique solution to this challenge. Here, we demonstrate the utility of the shape-shifting M13 phage template for nanomaterial morphological modification through the assembly of both gold nanowires and nanospheroids. Both peptide affinity and chemical-conjugation strategies are explored. The size and dispersity of the spheroid template were characterized with dynamic light scattering and transmission electron microscopy (TEM). In addition, TEM, energy dispersive spectroscopy and selected area electron diffraction were used to study the morphology, composition and crystallinity of the synthesized nanostructures. We have established the ability to shapeshift the M13 phage as a template for inorganic nanomaterials.

9171-31, Session PWed

Second harmonic generation from silver nanoparticles in aqueous solution with different protective agents

Minh Hoang Ngo, Isabelle Ledoux-Rak, Ecole Normale Supérieure de Cachan (France)

Nanometer-sized metallic colloidal particles with plasmonic resonances in the visible range display interesting and useful optical properties. Second harmonic generation (SHG) has emerged over the last decade as a powerful technique to measure the first hyperpolarizability tensor (?) of metallic nanoparticles [1]. Silver nanoparticles have showed potential applications in various fields such as environment, biomedicine, catalysis, optics and electronics etc. In this work, silver colloidal solutions have been synthesized rapidly in aqueous solution with different protective agent (PVP, PVA). By changing several parameters like the type and concentration of protective agent and the ratio of silver nitrate to NaBH4, we can control the particle size and morphology in these solutions. The ? values of Ag per atom and per particle for nanospheres at 1064 nm have been measured. Silver nanoparticles, which possess intense visible region surface plasmon absorption bands, prove to be excellent nonlinear scatterers.

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9171-34, Session PWed

Investigations of molecular nonlinear optical polarizabilities of azobenzenes substituted with strong acceptor groups

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Nonlinear optical (NLO) polymeric materials have attracted much attention due to their potential applications in the fields of optical information processing, optical sensing, and telecommunications [1]. Fundamentals for obtaining an efficient polymeric NLO material are: i) incorporation of highly polarizable chromophore; (ii) covalent bonding between chromophore and polymeric matrix in order to avoid phase separation and iii) high glass transition temperature to prevent chromophore relaxation [2]. In order to obtain better results optimization of the molecular hyperpolarizability should be done preliminary. Theoretical and experimental studies pointed out that hyperpolarizability value increase with the donor and/or acceptor strength [3]. Also, another key factor is the conjugation length of the molecule. The stronger the conjugation, the higher values for hyperpolarizability can be obtained.

Herein, azo-dyes with various substituents (cyano, nitro, methyl) and different substitution pattern were synthesized and characterized. The hyperpolarizability was determined using the solvatochromic method. A

correlation between donor/acceptor strength, substitution pattern and molecular hyperpolarizability was established, in order to maximize the NLO response of the final material.

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9172-1, Session Key

Low dimensional optics *(Keynote Presentation)*

François R. Flory, Ludovic Escoubas, Institut Matériaux Microélectronique Nanosciences de Provence (France); Gerard Berginc, Thales Optronique S.A.S. (France); Cheng-Chung Lee, National Central Univ. (Taiwan)

Thanks to progresses in material science and nanotechnologies, surfaces and thin films can now be structured at different scales. Photonics components take benefit of this possibility to fulfill still more and more complex functions. They are composed as well of organic as inorganic materials, dielectric, semiconductor, and metallic materials, or a mixture of them. Multiscale and chiral structures can be used to control both spectral, spatial distribution of light together with its polarization state. The optical mode density in the near field and in the far field can then be designed in particular by combining more or less resonant structures for the optical waves, associating diffraction, interferences and anisotropy like Fabry-Perot, waveguides, plasmons, photonic crystals, ... With the development of nanometer size structures another step is overtaken allowing the control of the intimate interaction of optical waves with materials to tune their basic electronic properties and permittivity.
Both optical and electronic properties are also strongly dependent on coupling effects needing a global approach. Artificially nanostructured materials often called metamaterials then exhibit new properties. Different phenomena recently considered, including optical topological insulator and structures for vortex waves transporting angular momentum of photons, will be also discussed and illustrated.

9172-2, Session 1

Collective resonant modes at a metasurface

Didier Felbacq, Univ. Montpellier 2 (France); Emmanuel Kling, Sagem (France); Emmanuel Rousseau, Richard Razafindrakoto, Univ. Montpellier 2 (France)

This work deals with the scattering of an electromagnetic wave by a structure that is made of a collection of wires that are very small in diameter with respect to the wavelength. All the wires are identical and have a resonant response to the electromagnetic field at specific frequencies. When they are organized periodically they show a collective electromagnetic behavior that can be tuned to control the scattering of light. The work gives an accurate description of this collective behavior. The method is essentially based on multiple scattering and asymptotic analysis. By using Bloch conditions, the expression of the diffracted field can be obtained as a function of the Bloch vector. The wavelength is not assumed to be small with respect to the period but only with respect to the diameter of the rods. Therefore the limit analysis is more general than a direct homogenization of the same medium. This allows us to describe the collection of rods as a surface, electromagnetically characterized by an impedance operator whose explicit form is given. For wavelength shorter than twice the period, the structure behaves as a grating and several diffracted orders appear. These orders carry electromagnetic energy characterized by the efficiency coefficient. Because of the resonances, these efficiencies possess a pole-and-zero structure than allows to tune the structure from perfectly reflective to perfectly transparent. A numerical study is carried, showing the various regimes that can be reached with this kind of metasurfaces. In particuliar, the Bloch diagrams are given for both resonant and non-resonant rods.

9172-3, Session 1

Design a symmetrical film stack as a negative index metamaterial

Yi-Jun Jen, Wei-Chih Liu, Ci-Yao Jheng, National Taipei Univ. of Technology (Taiwan)

In this work, the equivalent Herpin index and phase thickness of a symmetrical film stack (SFS) that comprises anisotropic dielectric film D and metal film M are analyzed using film matrix method. Three layered SFS DMD and five layered SFS DMDMD are investigated by setting the thickness of each film is 1/10 of wavelength. The positive real part of equivalent Herpin index and the negative real part of phase thickness lead to a negative real part of equivalent refractive index. The range of refractive indexes of D and M that would lead to negative index material is indicated here. When a polarized light wave propagates into the negative index material, the negative refraction and backward wave propagation occur. Since the structure is an anisotropic, the equivalent Herpin index and phase thickness are also polarization-dependent.
At certain wavelengths, the phase thickness is positive for one linear polarization but negative for the other orthogonal linear polarization. Therefore, large phase retardation due to large birefringence over unity is observed. The polarization-dependent passband and stopband of the SFS are also calculated to identify the possible wavelengths at which the SFS works as a polarization beam splitter.

9172-4, Session 1

Lateral patterned ion beam modification of vanadium dioxide for optical applications

Jura Rensberg, Sebastian Vatterodt, Friedrich-Schiller-Univ. Jena (Germany); Mikhail A. Kats, Shuyan Zhang, You Zhou, Harvard School of Engineering and Applied Sciences (United States); Ronny Nawrodt, Christian Schwartz, Marcel Hopfe, Tim Barth, Friedrich-Schiller-Univ. Jena (Germany); Shriram Ramanathan, Federico Capasso, Harvard School of Engineering and Applied Sciences (United States); Carsten Ronning, Friedrich-Schiller-Univ. Jena (Germany)

Vanadium dioxide (VO2) undergoes a reversible, ultrafast metal insulator transition (MIT) at a critical temperature TC of ~ 68°C. Associated with this transition are abrupt changes in resistivity, optical transmittance or reflectance covering a broad spectral range from visible to infrared. It is well known that the TC can be modified by the incorporation of dopants into the VO2 lattice. However, doping thin films during growth is limited to vertical incorporation of dopant profiles. In contrast, ion beam doping also allows for lateral doping using suitable masking techniques. Here, we report on the implantation of noble gas as well as light dopants into thin VO2 films. In any case, ion irradiation leads to a high concentration of defects created by the implantation process. This on one hand downgrades the MIT properties, but we will show in this presentation on the other hand that the induced strain also shifts the critical temperature to lower temperatures. Furthermore, thermal annealing at various temperatures and under different vacuum conditions, respectively, was applied resulting in a recovery of the crystal lattice and the incorporation of the doping species. The MIT characteristics of the films were investigated by resistivity measurements and optical spectrometry. Finally, lateral patterned ion beam doping profiles have been realized, which show new possibilities for designing detection devices, optical modulators, thermal emitters and absorbers.

9172-5, Session 2

Nanostructured thin films and their macrobehaviors *(Invited Paper)*

Cheng-Chung Lee, Mei-Ling Lo, National Central Univ. (Taiwan); Shih-Fang Liao, National Central Univ (Taiwan)

There are abounds of nanostructured thin films in nature and show fascinating features such as self-cleaning waterproof and attractive iridescence. The waterproof is due to hydrophobic microstructure, called as lotus effect and the low surface energy so that the surface is wax-

like. The iridescent color comes from a combination of interference of structural multilayers and the intrinsic properties of the layers. Among them, the wing of papilio blumei butterfly is of particular interesting. There are three key periodic structures. The micro-structures surface of the butterfly wing was mimicked by a nanoimprint process to get the hydrophobic characteristic. The iridescence green band and cyan tail of the wing on papilio blumei butterfly were investigated. The spectral change with thickness of chitin-air layers was simulated. 2D photonic-crystal model was applied to explain the change of reflectance spectra and color with angle. The structure of papilio blumei butterflies was fabricated successfully by three main techniques, PS spheres bedding, electron-beam gun evaporation and ICP etching.

9172-7, Session 2

Nano-structures for high intensity fiber laser applications

Andrew C. Y. Ngo, A*STAR Institute of Materials Research and Engineering (Singapore); Liying Hong, DSO National Labs. (Singapore); Z. Liu, A*STAR Institute of High Performance Computing (Singapore); R. F. Wu, DSO National Laboratories (Singapore); E. H. Khoo, A*STAR Institute of High Performance Computing (Singapore); J. H. Teng, A*STAR Institute of Materials Research and Engineering (Singapore)

High power fiber lasers are proposed to be a better candidate than conventional solid-state lasers for industries such as precision engineering since they are more compact and easier to operate. However, the beam quality generally degrades when one scales up the output power of the fiber laser.

One can improve the output beam quality by altering the phase of the laser beam at the exit surface, and a promising method to do so is by integrating specially designed nano-structures at the laser facets. In fact, this method was recently demonstrated – by integrating gold concentric ring grating structures to the facet of a quantum cascade laser, one observes significant improvement in the beam quality. Nevertheless, to improve the beam quality of high power fiber lasers using the method mentioned above, the material of the nano-structures must be able to withstand high laser fluence in the range of J/cm2.

In this work, we investigated the laser-induced damage threshold (LIDT) values of various materials for high power fiber laser applications. Consequently, we demonstrated that the shortlisted material and the fabricated nano-structures can withstand laser fluence exceeding 1.0 J/cm2.

9172-8, Session 2

Optically transparent, mechanically durable, nanostructured superhydrophobic/omniphobic/anti-fogging glass thin films

Tolga Aytug, Liu Tao, Andrew R. Lupini, Ilia N. Ivanov, Parans M. Paranthaman, David K. Christen, Oak Ridge National Lab. (United States)

It is difficult to obtain a transparent medium with a superhydrophobic coating that has high optical quality, mechanical durability, and can be fabricated at large scale with good uniformity. Traditional superhydrophobic coatings are soft in nature, with a Teflon-like surface chemistry, which results in reduced adhesion and durability. By combining vapor phase deposition together with methods to produce differentially-etched, nanostructured glass materials, we have overcome many of these common problems. Here we describe the formation of atomically bonded, optical-quality, nano-textured porous thin glass film coatings on glass plates, utilizing metastable spinodal phase separation in a low-alkali borosilicate glass system. As formed, these coatings are structurally superhydrophilic (i.e., display anti-fogging functionality) and demonstrate robust mechanical properties. After appropriate chemical surface modification, they exhibit exceptional superhydrophobic performance with water droplet contact angles reaching as high as 172o. As an added benefit, in both superhydrophobic and superhydrophilic states these nanostructured porous surfaces can block ultraviolet (UV) radiation and can be engineered to be anti-reflective with broadband and omnidirectional transparency. Moreover, by changing the chemical affinity of the surface, anti-smudge and omniphobic functionality of these films (i.e., repellency against various liquids) is also demonstrated.The approach offers a facile route to creation of commercially viable leading edge coated optical quality products for industrial applications.

9172-43, Session 2

PbS sculptured thin film and their effect on liquid crystals alignment

Ashok Chaudhary, Matvei Klebanov, Ibrahim Abdulhalim, Ben-Gurion Univ. of the Negev (Israel)

Lead Sulphide (PbS) thin films are prepared using glancing angle deposition (GLAD) by thermal evaporation and compared to the films prepared at zero angle. The morphology of the GLAD films clearly shows that anisotropic structure is obtained and composed of micro-sheets having sharp top edges (few tens of nm tip width). The structure of the zero degree deposited samples consist of a random network of connected nanowires with porosity as high as 80%. The Raman spectra of the zero degree films exhibit sharp peaks representative of vibrations in nano-crystalline PbS while these sharp peaks are absent in the spectra of the GLAD films.

Due to the orientational order of the GLAD PbS we decided to check its effect on the alignment of liquid crystals (LC) as one might expect strong effect to occur [1,2]. A nematic LC (BL036) device was prepared with one substrate covered by lead sulphide STF and the other substrate is covered with polyimide on indium tin oxide (ITO). The dark and bright states of the device have been observed between two crossed polarizers and found the alignment of the LC to be along the STF sheets orientation with good contrast. A lower threshold voltage was noticed in the device. Such type of composite devices may lead to new optical and photonics applications.

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9172-9, Session 3

New physics and applications of apertures in thin metal films *(Invited Paper)*

Reuven Gordon, Ahmed A Al Balushi, Abhay Kotnala, Ryan Gelfand, Skylar Wheaton, Univ. of Victoria (Canada); Shuwen Chen, Shilong Jin, National University of Defense Technology (China)

The nanoplasmonic properties of apertures in metal films have been studied extensively; however, we have recently discovered surprising new features of this simple system with applications to super-focusing and superscattering. Furthermore, apertures allow for optical tweezers that can hold onto particles ~1 nm; I will briefly highlight our work using these apertures to study protein - small molecule interactions and protein - DNA binding.

9172-10, Session 3

Nanostructured refractory thin films for solar applications

Emmanuel Ollier, Nicolas Dunoyer, Olivier Dellea, Helga Szambolics, CEA-LITEN (France)

The solar thermal sector needs very efficient thin film materials for solar radiation absorption. They are implemented on solar collectors included in solar receivers and are called selective materials because the required optical function depends on the wavelength range considered. Their reflectivity has to be minimized in the solar spectrum visible range to maximize the energy absorption. In the infrared range, their reflectivity must be maximized in order to reduce the infrared emissivity and the associated heat loss. The state of the art is mostly related to interferential multilayer films. Previous simulation work had shown that structured metallic surfaces could also allow a very good optical performance, opening the possibility to make them with refractory metals. But no process was available to realize the corresponding metamaterials. This work provides an original thin film, structured at both micro and nano scales. This double structuration provides a new and very efficient selective surface (absorption higher than 95% with less than 25% emissivity) based on a molybdenum refractory metamaterial. The electromagnetic simulations of the optical performances will be presented as well as the process flow based on thin film deposition, micromasking by a self-assembled layer and etching. The impact of the film deposition process and morphology in combination with an optimized etching step will be detailed. The optical characterizations in the visible and infrared ranges will be presented and compared to simulations at the nanoscale. The approach used opens prospects to realize micro-nanostructured films for various applications like optical management and superhydrophobic surfaces.

9172-11, Session 3

Ni/NiCrOx nanocomposite cermet as ideal candidate for solar thermal applications

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Solar absorbers are classified into six types [1]. Most commonly, the generic "tandem" absorber type is used, which consists of cermet (CERamic-METal) layers topped with anti-reflective (AR) layers. The cermet layer contains nanosized metallic particles embedded in a dielectric/transparent matrix. Concerning cermet layers deposited by magnetron sputtering, no evidence of this nanostructure was provided so far, although promising properties were previously established.

In this study, we first focus on the determining the nanostructure of NiCrOx layers. X-ray photoelectron spectroscopy (XPS) and X-ray diffraction (XRD) are used to get evidences of phase heterogeneity, crystallinity and grain size. For further assessment, transmission electronic microscopy (TEM) and high-resolution transmission electronic microscopy (HRTEM) are used to actually observe the nanostructure. Ni and NiO nanoparticles are found to be embedded in a NiCrOx matrix. This specific nanostructure is at the origin of remarkable optical properties of Ni/NiCrOx cermet material. As a demonstration of the potentialities of such a layer for solar absorbers applications, a layer of NiCrOx cermet was used in a tandem solar absorber stack, leading to solar absorptance as high as α=96.1% while keeping thermal emissivity as low as ε=2.2%. These results are compared with optical simulations, using refractive indexes determined by UV-visible and IR-ellipsometry. The above performances show that Ni/NiCrOx nanocomposite cermets are indeed ideal candidates for solar thermal applications.

[1] C.E. Kennedy, NREL technical report, July 2002.

9172-12, Session 3

Stretchable conducting materials with multi-scale hierarchical structures for biomedical applications

Hyun Kim, Bong Sup Shim, Inha Univ. (Korea, Republic of)

All of the conductive systems in human body such as central and peripheral neural networks, muscular and cardiomuscular systems are consisted with soft and stretchable materials. However, most of the artificial materials interfacing with those conductive systems such as neural electrodes, cardiac pacemakers have stiff mechanical properties. The rather contradictory properties between natural and artificial materials usually cause critical incompatibility problems in implanting body-machine interfaces for wide ranges of biomedical devices. Thus, we developed a stretchable and electrically conductive material with complex hierarchical structures; multi-scale microstructures and nanostructual electrical pathways. For biomedical purposes, an implantable polycaprolactone (PCL) membrane was coated by molecularly controlled layer-by-layer (LBL) assembly of single-walled carbon nanotubes (SWNTs). The soft PCL membrane with asymmetric micropores provides reversible stretching properties, while nano-thin SWNT coating preserves stable electrical conductivity even in a fully stretched state. This electrical conductivity enhanced ionic cell transmission and cell-to-cell interactions as well as electrical cellular stimulation on the membrane. Our novel stretchable conducting materials will overcome long-lasting challenges for bioelectronics applications by significantly reducing mechanical property gaps between artificial and natural body systems.

9172-13, Session 4

Engineering wavefront with Huygens, Fermat, Bragg, Friedel, and Fresnel laws *(Invited Paper)*

Zeno Gaburro, Univ. degli Studi di Trento (Italy)

We propose a metasurface that generalizes classical Snell and Fresnel laws, based on phase discontinuities. I provide an outlook on this structure, from different and complementary points of view, referred to classical Huygens, Fermat, Bragg, Friedel and Fresnel laws. The structure shows a generalization of the concept of crystallographic systematic absence. As a result, the Friedel law of crystals completely breaks down. A novel concept of "metacrystal" can be introduced, where systematic absences can be originated from form factors of meta-atoms, in contrast with natural absences, which are based on structure factors only. Applications will be also presented.

9172-14, Session 4

Computer-based numerical simulations of adsorption in nanostructures

Diana Khashimova, Technische Univ. Hamburg-Harburg (Germany)

Zeolites are crystalline oxides with uniform, molecular-pore diameters of 3-14Å. Significant developments since 1950 made production of synthetic zeolites with high purity and controlled chemical composition possible. In powder-form, zeolites are major role-players in high-tech, industrial catalysis, adsorption, and ion exchange applications.

Understanding properties of thin-film zeolites has been a focus of recent research. The ability to fine-tune desired macroscopic properties by controlled alteration at the molecular level is paramount. The relationships between macroscopic and molecular-level properties are established by experimental research. Because generating macroscopic, experimental data in a controlled laboratory can be prohibitively costly

and time-consuming, reliable numerical simulations, which remove such difficulties, are an attractive alternative.

Using a Configurational Biased Monte Carlo (CBMC) approach in grand canonical ensemble, numerical models for pure component and multicomponent adsorption processes were developed. Theoretical models such as ideal (IAST) and real adsorbed solution theory (RAST) to predict mixture adsorption in nanopores were used for comparison.

Investigative testing of the method on known materials, represented by all-silica zeolites such as MFI (channel type) and DDR (cage type), proved successful in replicating experimental data on adsorption of light hydrocarbons - alkanes, such as methane, ethane and butane. Additionally, adsorption of binary and ternary mixtures was simulated.

The given numerical approach developed can be a powerful, cost and time saving tool to predict process characteristics for different molecular-structure configurations. The approach used here for simulating adsorption properties of nanopore materials including process characteristics, may have great potential for other properties of interest.

9172-15, Session 4

Waves in tape helix loaded liquid crystal optical fiber

Masih Ghasemi, Pankaj K. Choudhury, Univ. Kebangsaan Malaysia (Malaysia)

Liquid crystals are non-homogeneous in nature, and also, these are optically anisotropic. Fibers made of liquid crystals have been greatly attracting owing to the interesting features that liquid crystals do exhibit. The investigation reported in this communication describes a rather new type of optical fiber structure composed of three layers with the outermost region being radially anisotropic liquid crystal, and the inner dielectric core-clad interface is loaded with conducting tape helix structure. Similarly to the case of sheath helix, the introduction of tape helix too would also throw the impact of alteration of the dispersion features of the guide. However, the situation becomes more complex in the sense that, apart from the helix pitch angle, the width of the tape helix structure becomes the additional factor to affect the dispersion characteristics. Further, to avoid computational complexities, the thickness of the introduced tape-like structure is considered to be nearly zero. We consider the core and the inner clad sections as made of linear, homogeneous and isotropic dielectrics, and the anisotropy remains in the outermost section due to the presence of nematic liquid crystal material. Taking into account a few low-order guided modes in the fiber structure, and considering the inclination of tape helix to be parallel as well as perpendicular to the optical axis (of the fiber), propagation characteristics are determined in terms of the relative power distributions. It is expected that the fiber structure would acquire a controlled dispersion characteristics, which would be of great use in many optical applications.

9172-16, Session 4

Shift happens: Optical sensing with Dyakonov--Tamm waves

Akhlesh Lakhtakia, The Pennsylvania State Univ. (United States); Muhammad Faryad, Lahore University of Management Sciences (Pakistan)

Now that the Dyakonov-Tamm surface wave has been experimentally detected, my aim is to show theoretically that this surface wave can be exploited for the optical detection of analytes in fluids. A Bruggeman formalism is harnessed for that purpose and two relevant boundary-value problems are solved.

9172-17, Session 4

Voigt waves in electro-optic homogenized composite materials

Tom G. Mackay, The Univ. of Edinburgh (United Kingdom)

In the usual case of optical propagation in a linear, homogeneous, anisotropic, dielectric material, two independent plane waves, with orthogonal polarizations and different phase speeds, can propagate in a given direction. However, in certain anisotropic materials, such as dissipative biaxial materials, there are particular directions along which these two plane waves coalesce to form a single plane wave. This coalescent wave is called a Voigt wave. Most conspicuously, the amplitude of a Voigt wave is linearly dependent upon propagation direction. In the present study, a homogenized composite material (HCM), which arises from an assembly two (or more) particulate component materials, is considered. By judicious choice of the component materials and their particulate shapes, it can be arranged for the HCM to support Voigt wave propagation whereas its component materials may not. If one of the component materials is an electro-optic material then an externally-applied DC electric field may be used to control Voigt wave propagation in the HCM. The extent to which Voigt wave propagation can be controlled via a DC electric field is explored theoretically here, using an approach based on the strong-property-fluctuation theory. This study has possible implications for applications in telecommunications, sensing and actuation.

9172-35, Session PWed

Direct light-induced surface patterning on thin films of amorphous chalcogenide

Ugis Gertners, Zanda Gertnere, Univ. of Latvia (Latvia)

The demand of lower cost surface-relief based optical instruments such as grating-based resonators or filters for waveguides, diffractometers, spectrometers, etc. is one of the main driving forces for the investigation of direct light-induced relief formation. The most common techniques for fabricating and investigating these surface-relief gratings involve an interferometric or holographic recording setup.

We have investigated that the light-induced mass transfer process strongly depends on the material itself and polarization of the light. The behavior of mass transfer and thus the resulting recording could be related to interaction between the polar photo-induced defects and the polarized electric field of recording beam. It has been shown that the mass transfer can be directed both ways – towards or away from the electric field intensity gradient. The evolution of surface relief in dependence from the recording time and polarization has been investigated in detail. The mechanism of the direct recording of surface relief on amorphous chalcogenide films based on the photo-induced plasticity has been discussed.

9172-36, Session PWed

Deposition condition influence on optical properties of indium tin oxide

Taras Ganulia, Olga Lopatynska, Vasyl Lendel, Leonid Poperenko, National Taras Shevchenko Univ. of Kyiv (Ukraine)

Indium tin oxide (ITO) is a solid solution of indium(III) oxid and tin(IV) oxide. It is applied for the production of transparent electrodes of liquid crystal screens, Organic Light-Emitting Diodes, touch screens.

We investigated the optical properties of thin films of indium oxide, produced by reactive magnetron sputtering with different deposition time. The unoxidized silicon was used as a substrate. Time of the films deposition was equal to 10-60 seconds.

Ellipsometric parameters were determined in a wide range of incidence angles by standard laser ellipsometer. The model of non-absorbing homogeneous layer on the absorption substrate (Si) was proposed to calculate the refractive index and ITO films thickness.

9172-37, Session PWed

Construction of 3D ordered macroporous thin films and their applications

Yao Li, Jiupeng Zhao, Harbin Institute of Technology (China)

We present the recent experimental investigation of 3D ordered structures, or photonic crystals (PCs) based on the functional materials, which are inhomogeneous materials whose dielectric properties vary periodically in space on a macroscopic scale. These ordered materials have novel and interesting properties concerning both basic physics and technological applications. For three dimensional photonic crystals, various techniques have been used including photolithography and etching techniques. Some of these techniques are already commercially available. To circumvent nanotechnological methods with their complex machinery, alternate approaches have been followed to grow photonic crystals as self-assembled structures from colloidal crystal. After a brief description of the main properties of photonic crystals, we present the self-assembly methods for the construction of photonic crystals with inverse opal structures by using colloidal cystal templates. The 3D PCs can be built with different building blocks and different materials, including semiconductors, alloys, metals, metal oxides and polymers. All these materials are very attractive for practical applications because it is possible to govern of their optical properties with the unique structure.

9172-38, Session PWed

Self-cleaning antireflective film for solar module glass

Wen Ding, Feng Yun, Deyang Xia, Jin Wang, Zhongxiao Song, Jinhai Si, Xi'an Jiaotong Univ. (China)

Solar cells technology has been developed quickly in recent years. There are a lot of factors affecting the solar cell's conversion efficiency, among which is solar radiation absorption. As we all know, most of the energy in solar radiation is concentrated in the wavelength range of 0.17~4 µm, in which there is 50% visible light, 43% infrared radiation, and 7% ultraviolet radiation. Silicon based solar cell has an optical light band gap of 1.1~1.7 eV, matching the visible light spectra. Due to the fact that silicon surface reflects visible light, it lead to a large loss of solar energy, limiting silicon based solar cell conversion efficiency no more than 30%. Many researches have been done to enlarge the silicon solar absorption spectra. In this paper, work has been conducted to introduce a nano antireflective (AR) solar glass with anti-reflective self-cleaning property, which is made up of nano SiO2 and TiO2.The TiO2-SiO2 anti-reflective self-cleaning composite film was prepared by sol-gel method using the network structure and low refractive index of SiO2 and self-cleaning effect of TiO2. Compared with the traditional SiO2 antireflective (AR), the film's hardness and weather resistance of the films was promoted significantly. The degradation of transmittance of the film after damp-heat test only 0.23%. The visible light transmittance of the film can be obtained at 98.81%. The average peak power output of solar module using antireflective glass was improved by 3.0% than that of uncoated ones.

9172-39, Session PWed

Effect of aging with partial discharges on the remnant breakdown strength of polypropylene films with natural and synthetic nanofillers

Md. A. Rab, Rohitha Dhara, Prathap Basappa, Norfolk State Univ. (United States); Anil Poda, Georgia Institute of Technology (United States)

Abstract: Literature indicates that electrical, thermal, mechanical or other characteristics of dielectric insulation can be improved significantly by homogeneously dispersing nanofillers into the polymer matrix. In this research work, comparative analyses of remnant breakdown strength (BDS) of natural and synthetic nano filled polypropylene (PP) films will be investigated. Two factors affect the breakdown characteristics of nano filled polypropylene films. These factors are changes in polymeric morphology and changes in carrier density and mobility due to the inclusion of nanofillers into the polymer matrix. Changes in these physical properties depend on nanofiller concentrations and type .In this experiment; continuous eight hours of ageing of every synthetic or natural nanofilled PP sample under a constant high AC voltage are being performed. Various nanofiller concentrations (e.g. PP-0%, PP-2% and PP-6% etc.) are being used in current experiment. During ageing; surface partial discharge parameters are being recorded after every five minutes. These data can be analyzed statistically. Next, for all aged and unaged samples a "Short Time" test will be performed with the application of a 60 Hz voltage cycle across the electrodes. Voltage will be applied starting from 0 V and increased at a rate of 667 v/s until a sample failure. Then, using a two parameters (scale factor, α and shape factor, β) Weibull distribution, breakdown strength analyses will be performed. In this case, scale factor indicates 63.2% cumulative probability of failure of the sample and Shape factor refers to the scattering of breakdown strength values. High β value means smaller spread in BDS and more reliability of dielectric behavior of the sample. Finally, a comparison between remnant breakdown strength of PP films with natural and synthetic nanofillers will be done.

9172-40, Session PWed

Ion beam sputtered Y_2O_3 anti-reflection coatings for far-infrared optics

Hongxiang Liu, Institute of Optics and Electronics (China); Ruzhen Liu, Institute of Optics and Electronics (China)

It was investigated that transition metal oxide anti-reflection(AR) coatings were prepared by ion beam sputter for far-infrared optics. Relative to other oxide films, yttria and ytterbia coatings have a good optical performance in far-infrared band. The ion beam sputtered Y2O3 thin films with a relatively thick single layer are amorphous, and extremely adherent to the ZnS and ZnSe substrates. The average transmission of Y2O3 double-side AR coatings on the ZnSe optics was about 93% in the 8-10 µm band. These AR coatings passed adhesion, abrasion,T/RH and salt fog tests, and meet the requirements of highly durable ZnS windows for infrared cameras.

9172-41, Session PWed

Gas sensing properties of ZnO nanoparticles decorated reduced graphene oxide composites synthesized by hydrothermal method

Gwiy-Sang Chung, Univ. of Ulsan (Korea, Republic of)

In this paper, reduced graphene oxide (rGO)/ZnO composites are synthesized using a simple precipitation method with GO and Zn(NO3)2.6H2O as precursors at 120 oC. The composites are characterized by Fourier transform infrared spectroscopy, X-ray diffraction patterns and scanning electron microscopy, and exhibited reduced GO layers decorated with tiny ZnO nanoparticles. Physical properties of the composites proved that the dispersion of rGO sheets within composites is key for achieving an excellent electrical and optical performance of the samples. Investigation of opto-electronic properties revealed near UV to blue photoluminescence (PL) and semiconducting behavior of bare ZnO and ZnO/rGO sheets. The electrical properties of the pure material to composition also showed increased conductivity markedly upon reduction due to partial restoration of graphitic structure. Gas sensing properties also investigated and results showed preferred selectivity to H2, CO gases with good response, good repeatability and reversibility within room temperature to 150 oC.

9172-42, Session PWed

Quantum mechanical investigation of Fermi energy under dimension quantization with thin films in nanostructured materials

Subhamoy Singha Roy, JIS College of Engineering (India)

In this paper, an effort is made to study the Fermi-Dirac distribution function in degenerate semiconductors forming band tails ( ) on the basis of a newly formulated electron dispersion law (is the well Fermi-Dirac function) and also it will be of much more interest, to investigate the Fermi-Dirac distribution function under the condition of carrier degeneracy, since it will help my revise in transport coefficients and electron dynamics in electronic devices made of degenerate semiconductors (n-GaAs as an example).

9172-18, Session 5

Local field enhancement effects for dielectric coatings on silver nanorod arrays *(Invited Paper)*

Yi-Jun Jen, Meng-Jie Lin, Ci-Yao Jheng, Wei-Chih Liu, National Taipei Univ. of Technology (Taiwan)

Oblique angle deposition has been applied to fabricate various anisotropic thin films to reach novel optical applications such as achromatic waveplate. It is easy to fabrication a dielectric anisotropic multi-layer according to the polarization-dependent optical filter design. A slanted silver nanorod array (NRA) could be deposited with glancing angle of deposition around 89°. It is interesting to investigate the optical performance by depositing dielectric materials upon silver NRA with tilt angle of 70° respect to the surface normal. By controlling the deposition angle, SiO2 and Ta2O5 grow on sliver rods in different morphologies. The first kind is to have dielectric rods stand on the tops of silver rods. The second one is form a multilayer partially or wholly upon the lateral side of each rod. The multilayer designed as high reflection filter (HRF) by arranging SiO2 and Ta2O5 alternatively on a cylindrical silver rod with diameter of 80nm and a length of 300nm would enhance the local field intensity when the rod is illuminated by s-polarized and p-polarized light waves. In this work, the effects of number and thicknesses of layers on the local field intensity are analyzed. The enhanced local field intensity increases as the number of HRF increasing. The associated optical properties including transmittance, reflectance, and extinctance of the capped NRA are also investigated theoretically. It is demonstrated experimentally that the intensity of light scattering from the capped NRA is also enhanced due to the local field confinement around silver rod.

9172-19, Session 5

Study of partial discharge characteristics of nano filled polypropylene films according to the variation in electric field distribution on the sample

Md. A. Rab, Rohitha Dhara, Prathap Basappa, Norfolk State Univ. (United States); Anil Poda, Norfolk State University (United States)

Literature indicates that incorporation of small amount of nano fillers into the polymer matrix of polypropylene (PP) film can improve its partial discharge endurance and breakdown strength .Partial discharge (PD) can occur due to the localized breakdown of a small portion inside the dielectric insulation or due to the electrical discharges which bridge the insulation partially. In this research, the effect of variation in applied electric field distribution on partials discharge characteristics of nanofilled PP films will be investigated. Also, how nano filler concentrations in polymer matrix influence the electric field endurance of PP film will be explored. Electric field distribution can be varied by changing the gap spacing between rod and plane electrodes using different gap spacers (1-3 mm).Samples will be attached with the plane electrode. High AC voltage will be applied on each sample during experiment and corresponding partial discharge parameters will be recorded. These data can be analyzed statistically and physically .PP films with various nano filler concentrations (0%, 2%, and 6%) will be used in these experiments. Gap spacing between rod and plane electrodes affects partial discharge parameters significantly. Partial discharge inception voltage, average discharge magnitudes and maximum discharge magnitude etc. will be varying due to the variation in gap spacing. Detail analyses of effect of variation in gap spacing and filler concentrations on PD characteristics will be performed.

9172-20, Session 5

Ultra-thin metal oxide based light controlled converter for sensing surface chemicals

Arunas Šetkus, Virginijus Bukauskas, Audruzis Mironas, Šarunas Vaškelis, Ctr. for Physical Sciences and Technology (Lithuania)

The thin film technology offers very attractive possibility to create a converter of the surface chemical changes into detectable signal at the ambient temperatures in the real time scale. The work mechanism makes the converter acceptable for a combination with the organic modifiers. In this study an ultra thin construction of metal oxide layers is sandwiched between the metal contacts and a system with the gas sensitivity that can be varied by the light is made and characterised. We analyse the possibilities to combine an influence of the surfaces and interfaces on the band structure and the electrical properties of the complete construction. The results demonstrate that the changes of the characteristics induced by the gas-surface interaction can be intentionally tuned by the modifications of the construction at the nanoscale. Due to the built in potential differences, the multilayered construction combines the photovoltaic effect and the conversion of the gas-surface interaction into electrical response. Our report describes some aspects of the response to gas of the multilayered structure at the ambient temperature without an external power source but with an adapted illumination. The response controlled by the light is associated with the arrangement of the multilayered construction in which the tunnelling current is assisted by the impurity electron states in the barrier area with the nanoscale width. The density of the states is dependent on the potential difference between the contacts and the parameters of the ambient temperature gas sensor can be intentionally determined by the thin film technology.

9172-21, Session 5

Magnetic, magnetooptical, and magnetotransport properties of Ti-substituted Co_2FeGa thin films

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Recently, much attention has been paid to the study of thin films of the Co-based Co2YX Heusler alloys which are of considerable practical interest due to a huge tunneling magnetoresistance and specific magnetotransport properties. Since most of the studies have been devoted to Co2MnX systems, it is of interest to explore properties of other Co2YX systems. Here we report on experimental study of magnetic, magnetooptical and magnetotransport of Co2(Fe,Ti)Ga thin films.

The Co2Fe1-xTixGa thin films were deposited on MgO substrate by a dual magnetron sputtering apparatus. Chemical composition of the films was controlled by the changing of the spattering power of the targets. Determined by inductively coupled plasma spectroscopy chemical composition of the films studied is (in at.%) Co50.3Fe20.3Ti5.6Ga23.8.

Magnetic, magnetooptical and magnetotransport properties of Co50.3Fe20.3Ti5.6Ga23.8 thin films were studied for the as-prepared as well as annealed samples. Measurements of transverse magnetooptical Kerr effect revealed that the spectral response of the films strongly depends on the structural ordering which can be manipulated by annealing conditions. Peculiarities in the magnetic properties of the films were attributed to the coexisting phases with different degree of structural disorder. Resistivity of the as-prepared thin films was found to be large, rho ~ 170 mu Ohm cm (at room temperature). Such a high resistivity is related to the structural disorder of the as-deposited thin films and, as a rule, rho significantly decreases after annealing due to structural ordering. Magnetoresistance of Co50.3Fe20.3Ti5.6Ga23.8 thin films was found to be linear in the fields above 1 T which is typical for half-Heusler systems as well as for Heusler-based ferromagnetic shape memory alloys.

9172-22, Session 6

Plasmonic and nanophotonic enhanced organic photovoltaics: breaking the power conversion efficiency barrier *(Invited Paper)*

Qiaoqiang Gan, Univ. at Buffalo (United States); Filbert J. Bartoli, Zakya H. Kafafi, Lehigh Univ. (United States)

Present photovoltaic technology offers a promising source of clean and sustainable renewable energy, but suffers from relatively high fabrication cost. Solar cell technologies are being actively pursued based on solution-processable organic photovoltaic (OPV) materials that can be sprayed like inexpensive paint or printed over large areas on rigid or flexible substrates. However, due to the poor electrical conductivity of most organic materials, OPVs are inherently very thin leading to poor solar light absorption, and low power conversion efficiency (PCE). Researchers have been working hard to develop new approaches to increase solar light absorption without altering the thicknesses of the OPV devices. In this talk, we will provide an overview of recent progress on plasmonic and nanophotonic enhanced OPVs, one of the most promising solutions for enhancing the PCE of an OPV device [1]. Focus will be on surface dispersion engineering and ultra-thin-film interference mechanisms which are compatible with thin-film devices [2]. A renewed focus on the science and technology of nanophotonics for light management and trapping in OPVs will lead to PCEs surpassing currently achieved performance levels.

Reference

[1] Q. Gan, F. J. Bartoli, Z. H. Kafafi, Plasmonic-Enhanced Organic Photovoltaics: Breaking the 10% Efficiency Barrier, Adv. Mater. 25, 2385 (2013) (front cover article).

[2] K. Liu, B. Zeng, H. Song, Q. Gan, F. J. Bartoli, Z. H. Kafafi, Super absorption of ultra-thin organic photovoltaic films, Optics Communications 314, 48 (2014) (invited paper).

9172-23, Session 6

Investigation into the effect of space charge on the surface erosion of synthetic and natural organoclay nanofilled PP films

Rohitha Dhara, Md. A. Rab, Norfolk State Univ. (United States); Prtahp Basappa, Norfolk State University (United States)

Due to the differences in dielectric constant and conductivities between nanofilled PP in comparison to base PP, it is postulated that the space charge formation and distribution in nanofilled samples is significantly reduced when compared to that of the base PP. However, the formation of space charge is reported to be different in PP with natural and synthetic organoclay nanocomposites. Abou Dakka and et.al investigated on the space charge formation in natural and synthetic organoclay nanocomposite filled PP when aged under constant electric field. It was observed that the space charge formed at the center of the electrodes reduced by half in nanofilled PP to that of base PP. It was also observed that when synthetic nanofilled samples and natural nanofilled samples are aged under similar conditions, the accumulated space charge in synthetic samples was more than in natural samples. Due to the accumulated space charge at the center of the electrodes, the occurrence of PDs is minimized leading to reduced surface degradation of samples. The focus of this paper is to study the PD behavior and defect volume through surface study of synthetic and natural organoclay nanofilled PP samples. This is studied by aging of natural and synthetic nanofilled filled samples with same percentage of filler content and for same duration of time. The results will be analyzed by performing surface study of aged samples under surface Profilometer and 3-D microscope.

9172-24, Session 6

Optical properties of porphyrin - graphene oxide composites

Harsha Vardhan Reddy Maraka, Rusul M. Al-Shammari, Nebras Al-Attar, Univ. College Dublin (Ireland); Sergio Lopez, Tia E. Keyes, Dublin City Univ. (Ireland); James H. Rice, Univ. College Dublin (Ireland)

A large amount of research effort has been applied to understand, control and apply the properties of graphene. One area that graphene has attracted interest is in optical materials. For example graphene and derivatives such as graphene oxide are known to be plasmonicly active making them attractive as materials in optically active composites for a range of different applications such as solar cells or optical emitters for cost effective displays.

In this work we aim to (via a non-invasive functionalization approach) tune and alter the intrinsic features of optically “transparent” graphene, by integrating water-soluble porphyrin aggregates. Porphyrin aggregates are well known to be optically active and have been applied to a range of optical applications. In our studies we explore the potential to combine porphyrin aggregates and graphene oxide to assess the advantages of such as a composite compared to the individual systems.

We apply a range of optical spectroscopy methods including photo-absorption, fluorescence and Raman spectroscopy to assess ground-state and excited state interactions. It is known that in the excited state, radical ion pair states are formed including the radical cation of the electron donating porphyrins and electrons that are delocalized within the basal plane of grapheme forming functional nanographene based charge-transfer hybrids. however no studies on porphyrin aggragates and graphene oxide composites have been reported. Our studies show that comparing resonant Raman scattering with optical transmission and fluorescence microscopy that the presence of influences the microscopic structures of the resulting composites.

9172-25, Session 6

High angular tolerant color filters based on subwavelength grating structures

Chenying Yang, Weidong Shen, Yueguang Zhang, Xu Fang, Beishi Chen, Xu Liu, Zhejiang Univ. (China)

We propose three color filters (cyan, magenta, yellow) based on a two-dimensional (2D) grating using a plasmonic metamaterial, which maintain the same perceived specular colors for a broad range of incident angles with the average polarization. Particle swarm optimization (PSO) method is employed to design these filters during the optimization procedure as described in the previous article. The transmission curves at different incident angles are coincident and the color difference calculated by CIE DE2000 is less than 2 for the incident angle up to 45°, within the threshold value of the human visual sense. That is to say, as the incident angle increases gradually, the reflected specular color changes much less than the multilayer filter in CIE1931 chromaticity diagram. Besides, the filters shows a stable optical property with the varying azimuth angle of the incident light. The electric field distribution of the structure is finally studied to analyze the principle of operation, which is attributed to the surface plasmonic resonance of the periodic metal surface topography. Angle-insensitive color filters with such excellent performance have an enormous potential applications in fields of special illumination, display and spectral analysis and so on.

9172-26, Session 7

Nanocrystalline cellulose thin films for optical encryption *(Invited Paper)*

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Nanocrystalline cellulose (NCC) exhibits unusual optical properties that make it of interest for hierarchical optical encryption in nanostructured films. The color-travel phenomenon of iridescence is exhibited by NCC when cast as a film from chiral nematic aqueous phase suspensions of the nanocrystals. In this presentation we discuss how this “iridescence by self-assembly” has potential for overt encryption as an anti-counterfeiting measure; and how it also offers an intrinsic level of covert encryption by reflecting left-circularly polarized light. We show that addition of a UV sensitive dye adds a third level of (covert) encryption, and that specially prepared films manifest a rare form of optical non-reciprocity that does not require the application of an applied field. Chirality parameters and stokes vector analyses suggest a simple authentication scheme. The method uses a UV light source and a circular polarizer in conjunction with an iridescent feature that can be verified by the eye or by chiral spectrometry.

9172-27, Session 7

Optical elaboration of nanostructure porous silica layer

Nicolas Desboeufs, Theirry Gacoin, Jacques Peretti, Jean-Pierre Boilot, Khalid Lahlil, Anh-Duc Vu, Lucio Martinelli, Yves Lassailly, Ecole Polytechnique (France)

Several spectacular photomechanical processes directly driven by the photo-isomerization transition of azobenzene type molecules have been investigated . These systems can be used in various technological applications, including photo-mechanics, diffractive optics, and micro- or nano-patterning. The cis-trans transition of the azobenzene is indeed accompanied by various changes of the material properties. An impressive example is the significant light induced surface mass transport. This phenomenon allows one-step inscription of high quality, photo-induced 1D and 2D surface patterns. Size and shape of this pattern can be easily tailored over a large scale ranging from a few tens of nanometers up to several microns by controlling the projected optical pattern. The originality of the process is that it’s an uncontacted and non-destructive reversible lithographic technique.

However, applications are limited by the strong azobenzene chromophores absorption in the visible range. Starting from our previous work on azobenzene doped sol-gel films , we report here a new and original method to remove all the organic chromophores while preserving the structuration. This method provides a new way to obtain uncolored and transparent pattern silica porous layer. Experimental results are supported by RCWA simulation to characterize the evolution of the pattern optical properties. Using this photoactive material it’s also possible to elaborate metal/dielectric hybrid 1D or 2D structures whose optical and mechanical properties can be controlled by light. Such hybrid system exhibits specific and interesting optical and plasmonic properties. Our results demonstrated a promising technique to reversibly elaborate hybrid nanostructured surface

9172-28, Session 7

Optical, electrical, and structural study of metallic nano-structured thin films fabricated by oblique angle deposition

Sung Jun Jang, Alireza Bonakdar, Hooman Mohseni, Northwestern Univ. (United States)

During last decade, there has been a long patient effort to find applications of oblique angle deposition. Many materials and structures have been explored to investigate their properties and potentials. Unless metallic nano-structures have an infinite amount of potential, still the metallic nano-structures formed by angle deposition are not sufficiently studied due to their structural limitation. Basically the angle deposition is based on directionality of vapor of physical vapor deposition so that the obtained structures from this technique should have also directional geometry. However, angle deposition is easy, fast and reliable process to fabricate nano-scale structures and there are some attractive applications to be investigated. One is highly transparent metallic thin films, which should be highly porous metallic films or metallic nano-rods but still connected each other. There are growing demands to have transparent but conductive film at level of metal film, which can be applicable to light harvesting and emitting devices as a low loss electrode. The other is superhydrophobic surfaces for ships’ hull coating. It can yield reduction of skin fraction drag for ships’ hull, thus increasing fuel efficiency. However, it is clear that the optical, electrical and structural investigation metallic nano-structure formed by angle deposition should precede for both applications.

In this report, we report metallic nano-structures fabricated by oblique angle evaporation. The optical, electrical and structural properties of metallic nano-structure were investigated. Dependency of various parameters governing metal evaporation was also explored. This report gives not only thoughtful understanding on metallic nano-structures formed angle deposition but also provides some ideas to engineer the properties of metal films for optoelectronic applications.

9172-29, Session 7

A solution to adhesion problem of oxide thin films on zinc selenide optical substrates

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This study was performed to bring a solution to the adherence problem between oxide thin film coatings and ZnSe substrates. ZnSe can be grown by Chemical Vapour Deposition (CVD) processes at high purity for optical applications. It can be easily shaped into the final form using

conventional grinding and polishing operations. Moreover, ZnSe has a high transparency (about 70%) within the 0.5 to 14 µm wavelength range which makes it an attractive candidate for dual band and laser applications. However, high refractive index of ZnSe (2.67) causes almost 30% of the incoming beam to be lost at the front and back surfaces due to reflection. In order to minimize these reflection losses, ZnSe is typically coated with multi-layered oxide thin films. During this study alternating high and low index layers were applied on the ZnSe substrates obtained from different vendors. Two different thin film deposition methods were utilize for this purpose, namely electron beam deposition and sputtering. All the samples were subjected to humidity and adhesion tests according to MIL-M-13508. We observed that prior to applying any heat treatment; oxide films exhibit a poor adhesion to the ZnSe substrates. In order to increase adhesion of these films, ZnSe samples were treated at 300C for varying amounts of time. Treated samples were examined in terms of their roughness, contact angle, morphology, refractive index, transparency, crystallography and chemical composition. We found that it is possible to manufacture durable thin film coatings on ZnSe, suitable for optical applications, utilizing well designed pre-treatment processes.

9172-30, Session 7

Mimumes for SUBTLE applications

Akhlesh Lakhtakia, The Pennsylvania State Univ. (United States)

Inspired by natural multifunctionality, mimumes are microfibrous multifunctional metamaterials.

Their microfibrosity engenders multifunctionality. The chief vehicle for initial research would be the poly(p-xylylene) polymers that are currently used in bulk non-fibrous forms for packaging and tribological applications in electronic and biomedical arenas. In microfibrous forms, these materials are expected to display simultaneous ultrasonic, biomedical, terahertz, light, and energy functionalities, thereby enabling the paradigm of design for system performance.

9172-31, Session 8

Bottom-up fabrication of non-close packed nanopillar arrays for photonic applications

Motofumi Suzuki, Shinta Suganuma, Yasuyuki Kaneko, Kyoto Univ. (Japan)

In order to control optical absorption and radiation, periodic nanostructures are required in the wide variety of technical fields. However, it is not easy to fabricate the periodic structures over a large area at low cost by using conventional top-down processes. Although self-assembly of polystyrene (PS) nanospheres is one of possible candidates to fabricate the periodic nanostructures, tunability of shapes and dielectric constants are quite limited. In this study, we report a novel bottom-up process to fabricate the periodic arrays of nanopillars, which can be applied to omnidirectional absorption in the VIS range and highly directive thermal radiation emission.

The periodic arrays of nanopillars were created by taking advantages of the oblique deposition technique. Monodispersed PS nanospheres of 0.2, 0.5 and 0.75 µm in diameter were self-assembled into a close packed monolayer by floating-transferring technique. On the PS nanosphere array, SiO_2 was evaporated up to 50 nm at a deposition angle α=70°, while the substrate was rotated inplane during deposition. Then, the samples were annealed in air of 600 °C for 1 h. As the result, the periodic array of SiO_2 nanospherical crowns was remained on the substrate surface. Using the array of the nanospherical crowns as the template, SiO_2, Ta_2O_5, Si or Ge were evaporated at α=80°. Well-isolated nanopillars of those materials grow just on the nanospherical crowns. Consequently, we have succeeded to develop the completely bottom-up process to fabricate well-isolated ordered nanopillars, which is robust in selection of composed materials.

9172-32, Session 8

Nanosculptured thin films of tungsten oxide

Tomas Tolenis, Ramutis Drazdys, Ctr. for Physical Sciences and Technology (Lithuania)

Sculptured thin films are anisotropic optical coatings. By varying the conditions and geometry of deposition, columnar, chiral and even more complex films can be made. By changing the structure of the coating, optical properties differ too. Columnar films have different refractive index in different directions, when chiral films are known for their selectivity for circular polarisation. Combination of those properties with the photochromism can open a new area for optical elements.

In this work, tungsten oxide (WO_3) is chosen as photochromic material. Sculptured thin films were formed using electron beam evaporation machine. Columnar thin films of this oxide were evaporated and anisotropy of refractive index measured by ellipsometer and spectrophotometer. Chiral sculptured thin films of WO_3 were also produced by rotating the substrate about its axis. Bragg phenomena was investigated of the films and showed the selectivity of circular polarisation. All the samples were also measured with SEM and XRD techniques. SEM photos showed the structures of films, when XRD measurements revealed the crystallinity and the grain sizes of material. Photochromism effect of tungsten oxide material was studied using Nd:YAG laser. The laser radiated UV light and the changes in the visible spectra were observed.

9172-33, Session 8

The effect of the substrate temperature and the acceleration potential drop on the structural and physical properties of SiC thin films deposed by TVA method

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Crystalline silicon carbide (SiC) thin films was prepared at substrate temperature between 200C and 600C using Thermionic Vacuum Arc (TVA) method. To increase the acceleration potential drop a negative bias voltage up to -1200V was applied on the substrate. The 200nm thickness carbon thin films was deposed on glass and Si substrate and then 200-500 nm thickness SiC layer on carbon thin films was deposed. The structure and physical characteristics of as-prepared SiC coating were characterized by Transmission Electron Microscopy (TEM, STEM) Energy Dispersive X-Ray Spectroscopy (EDS), Electron Scattering Chemical Analysis (ESCA), tribological technique, optical absorption technique and electrical conductivity measurement technique.

At a constant acceleration potential drop, the electrical conductivity of the SiC films deposed on C, increase with increasing of substrate temperature. On the other part, a significant increase in the acceleration

potential drop at constant substrate temperature lead to a variation of the crystallinity and electrical conductivity of the SiC coatings. In the region below the optical band gap the optical absorption increase with increasing of the crystallinity of the SiC. The optical absorption spectra of the structures was measured with a spectrometer Perkin Elmer Lambda 35 UV-VIS.

The tribological behavior of SiC coating was evaluated with a tribometer with ball-on-disk configuration from CSM device with 6 mm diameter sapphire ball, speed in dry conditions being 0.2 m/s, with normal contact loads of 0.5N, 1.0N, 1.5N, 2.0N, under unlubricated conditions. The friction coefficient on SiC was compared with the friction coefficient on uncoated carbon layer.

Electrical conductivity of the silicon carbide coating on carbon at different temperatures was measured comparing the potential drop on the sample with the potential drop on a series resistance in constant mode.

9172-34, Session 8

Tunable stoichiometry of SiOx-BaTiOy-BOz fabricated by multi-target PLD

John G. Jones, Jonathan T. Goldstein, Air Force Research Lab. (United States); Lirong Sun, General Dynamics Information Technology (United States); Jason C. Anders, Wright State Univ. (United States); Steven R. Smith, Gerald R. Landis, Univ. of Dayton Research Institute (United States); Chad M. Holbrook, Neil R. Murphy, Air Force Research Lab. (United States); Gregory Kozlowski, Wright State Univ. (United States); Rachel Jakubiak, C. E. Stutz, Air Force Research Lab. (United States)

Nanostructured thin-films of multiple oxide materials were obtained by using pulsed laser deposition (PLD) with independent targets consisting of Si, BaTiO3, and B. The novelty of this technique is that typically one would have to make a different target material (i.e. densify a ceramic mixture of powder having the correct mixture) for each different desired stoichiometry, but with independent targets and a synchronized high speed mirror system the stoichiometry can be tuned or graded as desired. Using an excimer laser, 248 nm, at a power of 300 mJ per pulse, island growth occurred on a per pulse basis with some 150 pulses required to deposit 1 nm of material. Programmable stoichiometry of multi-component or nanostructured thin-films was achieved by using a 248 nm KrF excimer laser, a galvanometer mirror system, and three independent target materials. The number of pulses on each target can be programmed with a high degree of precision. Trends in material properties were identified by systematically varying the stoichiometries of multiple nanostructured thin-films and comparing the resulting properties measured using in-situ spectroscopic ellipsometry, x-ray diffraction (XRD), and energy dispersive spectroscopy (EDS) (reliable with ~ 1 um of material thickness). Typically thin-films deposited by PLD at temperatures below 300 C are amorphous, however, crystallinity was obtained with post growth heat treatment and verified with XRD. Ideally trends in dielectric measurements and breakdown potential will be shown for different stoichiometries.

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9173-1, Session 1

Metrology for cellulose nanomaterials: update *(Invited Paper)*

Michael T. Postek, National Institute of Standards and Technology (United States)

Development of the metrology for advanced manufacturing of cellulosic nanomaterials (or basically, wood-based nanotechnology) is imperative to the success of this rising economic sector. Wood-based nanotechnology is a revolutionary technology that will create new jobs and strengthen America's forest-based economy through industrial development and expansion. It allows this, previously perceived, low-tech industry to leap-frog directly into high-tech products and processes and thus improves its current economic slump. Recent global investments in nanotechnology programs have led to a deeper appreciation of the high performance nature of cellulose nanomaterials. Cellulose, manufactured to the smallest possible-size (~2 nm x ~100 nm), is a high-value material that enables products to be lighter and stronger; have less embodied energy; utilize no catalysts, are biologically compatible and, come from a readily renewable resource. In addition to the potential for a dramatic impact on the national economy – estimated to be as much as $250 billion worldwide by 2020 – cellulose-based nanotechnology creates a pathway for expanded and new markets utilizing these renewable materials. The installed capacity associated with the US pulp and paper industry represents an opportunity, with investment, to rapidly move to large scale production of nano-based materials. It is conservatively estimated that a wood-based nanotechnology program would have a benefit to cost ratio of 25:1. However, effective imaging, characterization and fundamental measurement science for process control and characterization are lacking at the present time. This talk will discuss some of these needed measurements and potential solutions.

9173-2, Session 1

Development of a comprehensive metrology platform dedicated to dimensional measurements of CD atomic force microscopy tips

Johann Foucher, POLLEN Technology S.A.S. (France); Sebastian W. Schmidt, nanotools GmbH (Germany); Jérome Hazart, Aurelien Labrosse, Axel Largent, POLLEN Technology S.A.S. (France); Sandra Bos, CEA-LETI (France); Sebastian Schade, Bernd Irmer, nanotools GmbH (Germany)

Ever-shrinking feature dimensions in the semiconductor industry strongly drive the demands on CD metrology techniques and their measurement uncertainties. With the introduction of hybrid metrology, i.e. the approach to control process steps and parameters on the basis of complementary CD metrology systems, atomic force microscopy (AFM) has become more and more relevant as reference monitoring tool.

Over the last years, extensive improvements have been made on AFM tool stability and its abilities to serve as advanced 3D monitoring system. However, its applicability for CD features is still crucially determined by the AFM tip shape and dimensions.

The vital need for AFM tips applicable to critical device features thus requires highly accurate and precisely fabricated tip dimensions. With electron beam induced processing (EBIP) the current dimensional limitations given by state-of-the-art silicon etch technologies can be overcome. The reduction in tip dimensions, however, is accompanied by challenging demands on process control, quality inspection, and data extraction. With the ability to best meet these requirements, measurements are usually performed with dedicated CD-SEM tools allowing for optimized imaging at minimized contamination. However, whatever improvement is made on the CD-SEM regarding precision, real dimensions on the nanometer level extracted from free-standing 3D structures are hardly to obtain directly since its pretended accuracy remains ambiguous. As a consequence, only reference measurements, e.g. CD-AFM measurements, are able to fill the gap in order to reach the accuracy needed for an acceptable measurement uncertainty.

In this paper, we will present our most recent approach on the extraction of reliable tip dimensions from CD-SEM in order to answer future requirements on AFM tips. We demonstrate the capabilities of a newly developed, fully automatic analysis software based on advanced SEM image modelling and user a-priori knowledge integration in SEM image analysis algorithm. The impact of such breakthrough technology will be shown as a function of its stability and robustness by varying tip shape, imaging settings, and CD-SEM setup parameters. The extracted values are compared to data yielded from commonly used analysis approaches, and directly related to reference CD-AFM measurements. We will discuss the prospective challenges accompanied with shrinking tip dimensions and the potential of a comprehensive data fusion approach.

9173-3, Session 1

Recent advances of the metrological AFM at INRIM

Gian Bartolo Picotto, Roberto Bellotti, Istituto Nazionale di Ricerca Metrologica (Italy)

Quantitative measurements of nanostructured surfaces and particles are always frequently performed by metrological Atomic Force Microscopes (mAFMs). Several laboratories and manufacturers have developed their own design of mAFMs, all these characterized by their on-board metrology system and by the adopted opto-mechanical set-up. The non-linear motions, unwanted rotations, hysteresis and drifts of the moving elements are largely corrected by the on-board position sensors, mostly based on capacitive sensors, piezo-resistive elements and interferometers. In addition, the overall noise of the closed-loop system as well as the finite size and shape of the tip represents the other main sources of error in the reconstruction of the surface topography, namely when imaging high-aspect ratio structures at the nanoscale.

Some recent improvements of the instrument in use at INRIM for nanoparticles and surface metrology are discussed in this contribution. A new differential-type interferometric set-up has been developed to monitor and control the relative tip-sample z-displacements. The results of an internal comparison with step-height standards and reference artefacts are reported. Further, the characterization of the tip shape and size has been tested by using either reference nanoparticles and high-aspect ratio structures. Preliminary results including aspect ratio and curvature radius are outlined together with an upgrade of the own overall budget of uncertainty of the calibration of line-width standards.

9173-4, Session 1

Techniques for AFM tip characterization *(Invited Paper)*

Ndubuisi G. Orji, Ronald G. Dixson, National Institute of Standards and Technology (United States); Hiroshi Itoh, Chunmei Wang, National Institute of Advanced Industrial Science and Technology (Japan)

In atomic force microscopy (AFM) metrology, the tip is a major source of uncertainty. Images taken with an AFM show an apparent broadening

of feature dimensions. The resulting apparent feature in an image is a combination of the actual feature shape and the tip geometry. Parameters such as linewidth produce measurement results that include the added influence of the tip, and can be corrected if the tip width is known. Over the years, various methods and samples have been developed to extract the tip width and shape, and sometimes reconstruct the sample. We have a new tip characterizer for use with conventional and critical dimension AFM tips designed for size and shape evaluation. We model the characterization process with respect to CD-AFM tips, outline the type of evaluations that could be done and the types of uncertainty involved. We compared the measurement procedure and results with those obtained from a conventional tip characterizer. The comb characterizer when used in combination with current method provides more information about the quality of the tip.

9173-5, Session 2

Nanomanufacturing concerns about measurements made in the SEM Part III: vibration and drift *(Invited Paper)*

Michael T. Postek, András E. Vladár, National Institute of Standards and Technology (United States); Petr Cizmar, Physikalisch-Technische Bundesanstalt (Germany)

This is the third of a series of presentations discussing various contributions to the measurement uncertainty in scanned particle beam instruments and some solutions researched at NIST. The scanning electron microscope (SEM) has gone through tremendous evolution to become a critical tool for many and diverse scientific and industrial applications. These improvements have significantly improved the overall SEM performance and have made the instrument far easier to operate. But, ease of operation has also fostered operator complacency. In addition, the user friendliness has reduced the “apparent” need for more thorough operator training for using of these instruments. Therefore, this overall attitude has fostered the concept that the SEM is just another expensive digital camera or another peripheral device for a computer and that all of the issues related to obtaining quality data have been eliminated. Hence, a person using these instruments might be lulled into thinking that all of the potential pitfalls have been fully eliminated and they believe everything they see on the micrograph is always correct. But, as described in this and the earlier presentations this may not be the case. The first paper in this series, discussed some of the issues related to signal generation in the SEM, including instrument calibration, electron beam interactions and the need for physics-based modelling to accurately understand the actual image formation mechanisms. All these were summed together in a discussion of how these issues effect measurements made with the instrument. The second paper, discussed another major issue confronting the microscopist: specimen contamination and methods of contamination elimination. This third presentation discusses vibration and drift and some possible solutions. Over the years, workers at NIST have done a great deal of research into these issues in order to improve the fundamental metrology and some of this work is reviewed and discussed here.

9173-6, Session 2

Developing detection efficiency standards for atom probe tomography

Ty J. Prosa, Brian P. Geiser, Dan Lawrence, David Olson, David J. Larson, CAMECA Instruments, Inc. (United States)

Atom Probe Tomography, (APT) is a near-atomic-scale analytical technique, and due to recent advances in instrumentation and sample preparation techniques, APT is being used on a variety of increasingly challenging 3D applications [1].

Total system detector efficiency is a key parameter for 1) estimating system performance, 2) understanding the detection of low concentration species and small clusters of atoms, and 3) accurate reconstruction of atomic coordinates from detected ions; however, its experimental determination can be complicated. The techniques used to date provide limited precision and unknown accuracy because alternative means have not been reported [2]. These methods utilize the atomic periodicities observed in data and require significant data manipulation where each step may be prone to biasing the end result.

This work explores new practical ways to measure total system detector efficiency as well as the necessary specimen characteristics. By utilizing APT analysis of known volumes of material, a high quality measurement of the volume dimensions allows for estimation of the number of atoms within the volume. Adequately encapsulating these volumes ensures that all the field evaporated ions are incident on the detector. The simple ratio of the expected number of atoms to the detected number of atoms then provides a direct measurement of efficiency. We present efficiency measurements based on NIST SRM 2135c encapsulated in silver and nickel as well as progress on alternate materials and encapsulations.

[1] T.F. Kelly and D.J. Larson, Ann. Rev. Mat. Res. 42 (2012) 1.

[2] B.P. Geiser et al., Microsc. Microanal. 13 (2007) 437.

9173-7, Session 2

Recent advances in scanning microwave impedance microscopy (sMIM) for nano-scale measurements and industrial applications

Stuart Friedman, Oskar Amster, PrimeNano, Inc. (United States)

The development and manufacturing of commercially viable nano-materials and nano-devices requires detailed knowledge not only of topography, but increasingly also of electrical properties. Measurement of permittivity and conductivity is well established at modest dimensions, but characterization of local electrical properties, for sub-micron and/or inhomogeneous samples, remains challenging. Scanning probe microscopies, such as AFM, have found significant research and industrial use for imaging and quantifying morphology and mechanical properties at the nano-scale. Electrical measurement modes such as conductive AFM, Kelvin probe force microscopy, and scanning capacitance microscopy have had some success in measuring electrical properties at the nano-scale; however, each technique is often limited to a subset of materials or samples.

Scanning Microwave Impedance Microscopy (sMIM), a new electrical measurement mode for AFM, has shown significant success in the imaging and characterization of electrical properties at 10’s of nm length scales. In this talk we will introduce the principles of operation for sMIM and review the state of the art, including imaging studies revealing electrical characteristics of novel materials and nanostructures, such as composites, graphene, patterned optical crystals and ferro-electrics. In addition to imaging, the technique is suited for a variety of metrology applications where specific physical properties are determined quantitatively. Examples include the measurement of dielectric constant (permittivity) and conductivity (e.g. dopant concentration). These capabilities will be presented, illustrating sensitivity and resolution for dielectric constant, doping levels and capacitance. For samples where properties such as dielectric constant are known the technique can be used to measure film thickness.

9173-8, Session 3

Standardization of methods for extracting statistics from surface profile measurements *(Invited Paper)*

Peter Z. Takacs, Brookhaven National Lab. (United States)

Surface profilers and optical interferometers produce 2D maps of surface and wavefront topography. The Power Spectral Density (PSD) function of the surface height distribution is a powerful tool to assess the quality and performance of the surface in question. In order to extract useful information about the spectral distribution of surface roughness or

mid-spatial frequency error over a particular spatial frequency band, it is necessary to first detrend the raw data and apply a window function before computing the PSD. This process eliminates discontinuities at the borders of the profile that would otherwise produce large amounts of spurious power that would mask the true nature of the surface roughness. This procedure is now part of a new draft standard that is being adopted by the US OEOSC for statistical analysis of optical surface data, OP1.005. Illustrations of the usefulness of this procedure will be presented.

9173-9, Session 3

Improved quality control of silicon wafers using novel off-line air pocket image analysis *(Invited Paper)*

John F. Valley, SunEdison (United States); M. Cristina Sanna, SunEdison Italy (Italy)

Air pockets (APK) occur randomly in Cz grown crystals and may become included in wafers after slicing and polishing. Previously the only APK of interest were those that intersected the front surface of the wafer and therefore directly impacted device yield. Mobile electronics have placed new demands on wafers to be internally APK-free for reasons of thermal management and packaging yield. We present a novel, recently patented, APK image processing technique and demonstrate the use of that technique, off-line, to improve quality control during wafer manufacturing. The APK, which occur only rarely within a finished wafer, are detected using in-line automated inspection equipment. The in-line equipment currently sorts for APK using metrics derived from camera images. First, the APK-suspect blob is found in the image based on a threshold image intensity. From then on the APK-suspect image data is treated as black and white (B&W) blob data. Metrics are extracted from the B&W image to quantify the circular nature of the blob's area. Other than thresholding, the image intensity information is not used directly in determining the APK metrics, therefore image judgment may occasionally be adversely impacted. However, the images are saved as monochrome 8-bit image files and are available for post-processing off-line. We present here a new set of APK image metrics based on image symmetry using the in-line saved images. Using automated off-line analysis these new metrics are shown to improve sort accuracy and purity when compared to human image judgment. The new metrics are shown to be particularly useful as the APK-suspect blob size gets smaller and pixelation effects make the B&W derived metrics less robust.

9173-10, Session 3

Interferometric measurement of dimensional and thermal stability of joints

Hagen Lorenz, René Schödel, Physikalisch-Technische Bundesanstalt (Germany)

At PTB, the most precise interferometric length measurements with sub-nanometre precision are carried out under vacuum conditions, using an instrumentation similar to regular gauge block (GB) interferometers. Repeated length measurements provide information about the intrinsic stability of the GB which can be affected by internal structural changes of the material. Such processes can also be triggered by external events like thermal or mechanical loading. Due to growing demands in precision engineering, there is a need to investigate not only the stability of materials but also of joints. The dimensional and thermal stability of joints, produced with techniques like gluing and screwing, has been investigated for the fist time over a long-term period in the range of months to years and with a precision as available for GBs.

We describe representative joints made of GBs and appropriate techniques that we have developed to exploit the parallelism of GB surfaces in order to achieve sub-nanometer accuracy of interferometric measurements. Dependent on the measurement task, the stability was measured longitudinally or laterally to the connection interface, i.e. the GBs had been joined at the front faces or at the side faces, respectively. Additional to the length, also the surface orientations of the joints were detected by analysis of the phase topographies.

With the use of the sample joints, elements frequently used in precision engineering can be examined carefully. It should be possible also to adapt the specimens with respect to specialized joining techniques applied in ultra precision instruments.

9173-12, Session 4

Refractometry of turbid nanoparticle suspensions and applications

Augusto García-Valenzuela, Humberto Contreras-Tello, Univ. Nacional Autónoma de México (Mexico)

To date only the measurement of the refractive index of homogeneous materials is well established. However, many materials of technological and scientific significance are not homogeneous at a scale comparable to visible wavelengths. In such cases, light traveling within the material gets scattered and some portion of it, or all of it, becomes diffuse. In these cases the medium is turbid and has an effective refractive index that is a complex quantity even if there is no absorption of light. There is a great potential of novel applications of a robust refractometry of turbid nano- and micro-particle suspensions. It has been recently shown that measurements of the complex effective refractive index can be used advantageously to determine particles' size, refractive index and concentration.

In this work we propose an improved device to obtain angular-intensity profiles around the critical angle of diffuse light transmitted from a turbid sample into a transparent prism. The sample is illuminated by a laser beam incident to the sample at a variable angle of incidence from the prism side. The refractometer enables us measuring the refractive index of particles suspensions of higher turbidity than in previous works. We use the refractometer to test a recently developed theoretical model and find very good agreement with experimental data. Overall, our objective is to establish on firm grounds a methodology for measuring the refractive index of turbid particle suspensions using the refraction of diffuse light around the critical angle and use it to characterize nano- and micro-particles in suspension.

9173-13, Session 4

Study of internal energy flows of a coma affected singular beam by Helmholtz Hodge decomposition

Monika Bahl, P. Senthilkumaran, Indian Institute of Technology Delhi (India)

We introduce an efficient and simple technique to determine the topology of singular optical beams. It is based on the Helmholtz Hodge Decomposition (HHD) of the focused structure of coma infused singular beams. The HHD segregates the phase gradient structure of an optical field into explicit solenoidal and irrotational components. A study of the Poynting vector or optical currents in the segmented divergence free component reveals the points of singularities formed along with their helicity, at the focal plane. A study of this power flow or energy circulation is important when one deals with set ups as in optical tweezers, optical micro-motors and spanners where the beams are focused by an optical lens. Minor perturbations like aberrations affect the energy flow in the focal volume. Our analysis segments the focal volume field structure into an explicit curl and a divergence component. The Poynting vector analysis in these parts reveals the topology of the input singular beam along with the energy flows at the focal plane. In this work, we concern ourselves with the former results. Fresnel-Kirchoff diffraction integral is numerically evaluated to determine the focal plane structure of the beam after it has been infected with coma aberration at the exit pupil of the lens. Results indicate a flattening of the dark core in the intensity patterns and the effect seems to be more pronounced as the charge

of the singular beam increases. The extracted information from the decomposed structures reveals the charge and the helicity of the input beam.

9173-14, Session 4

Mass sensing AlN sensors for waste water monitoring

Ryan Porrazzo, Graham Potter, Leigh K. Lydecker IV, Z. Foraida, Suhasini Gattu, Natalya Tokranova, James Castracane, SUNY College of Nanoscale Science and Engineering (United States)

Monitoring the presence of nanomaterials in waste water from semiconductor facilities becomes an important task for public health organizations. Advanced semiconductor technology allows fabrication of sensitive mass piezoelectric sensors which are able to detect less than 10 µg/L of nanomaterials such as nanoparticles of alumina, amorphous silica, ceria, etc. The interactions between acoustic waves generated by the piezoelectric sensor and nanomaterial mass attached to its surface define the sensing response as a shift in the resonant frequency. In this article the AlN film bulk acoustic resonator (FBAR) development and characterization are presented. Tilted c-axis oriented AlN films were deposited by a DC reactive magnetron sputtering to generate shear waves which don't propagate in water and thus the acoustic loses are reduced. The high acoustic velocity of AlN over quartz allows the increase in resonance frequency in comparison with a quartz crystal microbalance (QCM) and results in a higher frequency shift per mass change, or greater sensitivity. The membrane and electrodes were fabricated using a standard semiconductor technology. The surface device functionalization was performed to obtain selectivity towards a specific nanomaterial. As a result, the devices were covered with a "docking" layer that allows the nanomaterials to be selectively attached onto the surface. The different functionalization techniques were used and analyzed, such as electro-polymerization, layer-by-layer deposition, etc. The influence of the coating thickness on the sensitivity for mass detection was studied. The observed frequency shift for a certain mass load increases proportional to the resonance frequency squared.

9173-16, Session 4

Shack-Hartmann waveffront sensor non-null testing off-axis aspheric mirror on axis

Jinping Zhang, Shanghai Institute of Technical Physics (China); Zhongyu Zhang, Xue-jun Zhang, Changchun Institute of Optics, Fine Mechanics and Physics (China)

At the end stage of the grinding and rough polishing a reflection mirror, the shape of the surface usually deviates from the target one. Especially when the mirror has a steep aspheric surface, contact profilometer may not be possible or correct. The Hartmann test has a great advantage in larger dynamic range compared with interferometer. It means that the mirror can be tested with a Hartmann wave-front sensor without null compensator. This paper presents a new method that using Shack-Hartmann wave-front sensor to non-null test off-axis aspheric surface on axis, and analyzes the impact on test results by error source and misalignment. Using a simulated wave-front, testing an off-axis aspheric reflection mirror is carried out. This mirror is also tested by contact profilometer and interferometer. Comparing the three testing results, the Shack-Hartmann testing is not only more accurate than profilometer, but also has a larger dynamic range than interferometer. It also shows that the theory of testing system and separation of errors are correct.

9173-15, Session PWed

High-resolution optical measurement technique for diffraction gratings by using a variable angle phase modulation ellipsometer

Kyongseok Kim, Bo Ram Kim, Sung-Ho Lee, Seung-Han Park, Yonsei Univ. (Korea, Republic of)

In semiconductor industry, optical metrology is becoming a promising technique, replacing conventional measurement methods such as SEM and AFM. For instance, ellipsometric spectra obtained at a fixed angle of incidence (AOI) have been frequently used to extract geometric parameters of the nano-patterned structures. In this presentation, a variable angle ellipsometer to determine the geometrical parameters of diffraction gratings with good AOI precision is demonstrated. Our technique is based on the configuration of reversing the independent variable, i.e., varying AOI's at a fixed wavelength, which utilizes the sensitive dependence of the sidewall angle on AOI's.

A phase modulation ellipsometer (PME) with a monochromatic light source (He-Ne laser) is constructed and automatized by motorized stages with high precision. After optimizing the alignment, AOI can be controlled within 0.01°. The diffraction gratings with slightly varying geometrical parameters (height, width, and sidewall angle) are prepared and their ellipsometric angles (EAs) with scanning AOI are measured. The best fit to the measured EAs is acquired via parameterized nonlinear regression in rigorous coupled-wave analysis algorithm. The results show that the geometric parameters of the diffraction gratings can be successfully obtainable, indicating potential application of PME to analyze the independent variables of the optical metrology.

9173-17, Session PWed

Quantifying ellipsometric data uncertainties for multichannel rotating-element ellipsometers

Yong Jai Cho, Won Chegal, Hyun Mo Cho, Korea Research Institute of Standards and Science (Korea, Republic of)

The multichannel spectroscopic ellipsometers are well known as a real-time diagnostic tool in science and industry of surfaces, thin films, and nano patterns. The rotating-element ellipsometric configurations have been adopted widely for the multichannel spectroscopic ellipsometers. The requirements for enhancing ellipsometric accuracy become more stringent especially in the semiconductor industries but there is no generally accepted method for characterizing or quantifying ellipsometric data accuracy [1]. In the real spectroscopic ellipsometers, there are temporal random noises due to stochastic fluctuation in the exposures measured during a given integration time by a pixel or binning pixel group in the CCD arrays. Using a novel ellipsometric data acquisition method [2], we analyzed experimentally the error propagation from the measured Fourier coefficients of the irradiance waveform to the ellipsometric sample parameters [3]. In this presentation, we show that the closed-form expressions of ellipsometric sample parameters can be evaluated from the Fourier coefficients using the method of least squares. To quantify the ellipsometric data uncertainties due to the random noises, we obtain the standard deviations and correlation coefficients of the unnormalized Fourier coefficients formulated analytically for the novel data acquisition method and then analyze the error propagation from the measured exposures to the ellipsometric sample parameters.

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9173-18, Session PWed

Scatterometric characterization of diffractive optical elements

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Characterization of diffractive optical elements using invasive methods such as scanning electron microscope (SEM) or atomic force microscope (AFM) is slow and potentially destructive to the element. However, applying scatterometric method the measurements are not only fast but also the sample remains intact. Because of these advantages, scatterometer would be also be an ideal tool for online quality control of the fabrication processes. The scatterometric method, on the other hand, introduces an inverse problem which can be time consuming to solve at least for complex structures.

In this work we have analyzed a binary grating and a binary 1-to-5 beamsplitter which were measured using a laser diffractometer modified for high angular resolution detection of the intensities of diffraction orders. The binary samples were measured using several wavelengths and incidence angles in both TE and TM polarizations to ensure that the amount of data is sufficient to for the inverse problem. The inverse calculations were performed by applying Fourier modal method together with conventional optimization algorithms. After the solution of the inverse problem, the obtained dimensional parameters of the gratings were compared with the parameters determined from AFM measurements.

The correlation of the results was very good for the binary structure which confirms that the scatterometric method is capable of determining the parameters of the gratings. The results for the beamsplitter were also very promising which shows that the method also works for more complex structures.

9173-19, Session PWed

Precision analysis of three polarizer spectroscopic ellipsometer

Won Chegal, Yong Jai Cho, Hyun Mo Cho, Korea Research Institute of Standards and Science (Korea, Republic of)

We developed a spectroscopic ellipsometer based on a three polarizer configuration composed of a white light source, a fixed polarizer, a rotating polarizer, a sample, a fixed analyzer, and a multichannel spectrometer in order to investigate the precision optimization of real-time rotating-element spectroscopic ellipsometers. A novel Fourier analysis algorithm, i.e., the discrete Fourier transform of the measured exposures, was adopted to obtain the Fourier coefficients accurately and precisely, in contrast with the only data acquisition method used previously. From the spectra of the normalized Fourier coefficients experimentally obtained using the novel Fourier analysis, the offset angles of the fixed polarizer, rotating polarizer, and fixed analyzer were determined by regression calibration, and their values were almost constant, independent of the wavelengths used. The excellent fits to the experimental spectra of the ellipsometric sample parameters strongly suggest that the real-time spectroscopic ellipsometer based on the three-polarizer design is very reliable and that the precision of the data reduction functions represented in terms of the three Fourier coefficients was considerably enhanced compared with the commonly used data reduction functions. This approach will be helpful for analyzing the optimization of the precision of other types of rotating-element ellipsometers.

9174-1, Session 1

Formation of vertical MnAs/InAs heterojunction nanowires *(Invited Paper)*

Shinjiro Hara, Hiromu Fujimagari, Shinya Sakita, Hokkaido Univ. (Japan)

No abstract available

9174-2, Session 1

Nanoprobe electrical measurements of single nanowire structures *(Invited Paper)*

Simon Watkins, Simon Fraser Univ. (Canada)

No abstract available

9174-3, Session 1

Van der Waals epitaxy of InAs nanostructures on graphene *(Invited Paper)*

Young Joon Hong, Sejong Univ. (Korea, Republic of); Takashi Fukui, Hokkaido Univ. (Japan)

Unconventional, noncovalent heteroepitaxy of inorganic semiconductors is of importance for making use of graphene as epitaxial substrates. The van der Waals (vdW) heteroepitaxy has been developed firstly by Koma since 1984. In this talk, the vdW InAs/graphene heterostructures, fabricated by metal–organic vapor-phase epitaxy, are presented. The critical factors leading to nucleation and growth for the vdW heteroepitaxy of inorganic semiconductor nanostructures on honeycomb carbon surface are presented in terms of lattice misfit and surface potentials. Importantly, the vdW heteroepitaxy enabled to grow InAs nanowires vertically aligned on single-layer graphene, implying that the vdW attraction is strong enough to grow vertical nanostructures with high aspect ratio. We also demonstrate the world thinnest substrate material, that is single-layer graphene. Moreover, suspended single-layer graphene was utilized for verifying the role of monoatomic layer as substrates for vdW epitaxy, yielding vdW epitaxial double heterostructures. We also present the controlled vdW epitaxy method for high-yield and uniform InAs nanowire arrays on graphene by utilizing substrate surface etching and patterning techniques. Our work provides a new important methodology and principles of fabricating the graphene-based epitaxial semiconductors for new functional electronic and optoelectronic device applications.

9174-4, Session 1

Direct band gap wurtzite GaP nanowires for LEDs and quantum devices *(Invited Paper)*

Simone Assali, Technische Univ. Eindhoven (Netherlands); Dominik Kriegner, Institute of Semiconductor and Solid State Physics, Johannes Kepler University (Austria); Ilaria Zardo, TU/e Eindhoven (Netherlands); Sebastien Plissard, CNRS, LAAS (France); Marcel M. A. Verheijen, Philips Innovation Services Eindhoven, High Tech Campus (Netherlands); Julian Stangl, Institute of Semiconductor and Solid State Physics, Johannes Kepler University (Austria); Erik P Bakkers, Technische Univ. Delft (Netherlands); Jos J.E.M. Haverkort, TU/e Eindhoven (Netherlands)

Theoretical band structure calculations for Gallium Phosphide (GaP) predict a direct band gap when this material is grown with the wurtzite (WZ) crystal structure [1-2]. Here, we discuss the growth of GaP nanowires with high-purity WZ crystal phase. Photoluminescence (PL) measurements will be shown to demonstrate the direct nature of the band gap [3]. In order to provide a deeper understanding of the band structure of the WZ GaP nanowires, polarization-dependent PL and Photoluminescence-excitation (PLE) measurements on transferred nanowires will be discussed. This allows us to address the nature of the optical transitions with respect to the theoretical predicted values [1-2] and the expected selection rules for the WZ phase [4]. Temperature-dependent PL-PLE scans reveal the excitonic nature of the optical transitions, together with room-temperature emission. Thus, WZ GaP nanowires are a promising candidate to solve the problem of the green gap in white LEDs technology [5]. Furthermore, WZ GaP nanowires could be used as building blocks for the solid state quantum systems. The control of the switch between the WZ and the zinc-blende (ZB) crystal structure over an atomic scale will be discussed, resulting in the formation of atomically sharp crystal phase quantum dot (CPQD) structures[1-2] along the nanowire length.

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9174-5, Session 1

Development of III-V compound semiconductor nanowire array solar cells *(Invited Paper)*

Lan Fu, Q. Gao, Yesaya C. Wenas, Z. Li, Yu-Heng Lee, Fan Wang, Sudha Mokkapati, Hark Hoe Tan, Chennupati Jagadish, The Australian National Univ. (Australia)

No abstract available

9174-6, Session 2

Silicon epitaxy in nanoscale for photovoltaic applications *(Invited Paper)*

Jinkyoung Yoo, Los Alamos National Lab. (United States); Shadi A. Dayeh, Univ. of California, San Diego (United States); Wei Tang, Univ. of California, Los Angeles (United States); Norman C. Bartelt, Sandia National Labs. (United States); Alp T. Findikoglu, Samuel T. Picraux, Los Alamos National Lab. (United States)

Epitaxial growth of silicon (Si) radial shell on Si nanowire will be presented. Single crystalline Si radial shell growths were conducted on core Si NWs. The dimensions of the core Si NWs were precisely controlled by lithographic techniques and Si deep reactive ion etching followed Crystalline 3D Si growth was performed by low-pressure chemical vapor deposition (CVD) growth. Atomically smooth Si template surfaces of NWs for 3D epitaxy were prepared by multi-step thermal oxidation and wet oxide etching. The single crystalline doped and undoped Si layers were grown in the range of 670 to 800oC to avoid autodoping issues at high growth temperatures. The growth rate and crystallinity of grown Si layers were investigated by scanning and transmission electron microscopy. Through a series of characterizations we observe an unprecedented dependence of growth rate of the single crystalline Si layers along the radial direction on initial diameter, which cannot be explained by the Gibbs-Thomson effect. We also discuss the effect of dopants on the epitaxial growth rate and discuss the growth mechanism of single crystalline Si radial shells at nanoscale dimensions.

Additionally, morphological evolution of 3D Si and critical thickness behavior will be discussed. Comprehensive studies reveal that judicious control of shell layer thickness enables us to get advantages of enhanced optical absorption and carrier generation under sun illumination in Si radial p-i-n junction. The epitaxial approach for radial shell formation will be useful for high performance photovoltaic device applications.

9174-7, Session 2

ZnO nanostructures: from material to systems *(Invited Paper)*

Mehdi F. Anwar, Univ. of Connecticut (United States)

Zinc oxide (ZnO) is a unique wide bandgap biocompatible material system exhibiting both semiconducting and piezoelectric properties while the nanostructures providing a diverse group of growth morphologies. In this talk we will discuss the growth and characterization of ZnO nanowires, nanorods and heteroepitaxies. Applications ranging from UV detection, energy harvesting and resistive random access memories will be prtesented.

9174-8, Session 2

Structural and electro-optical properties of one-dimensional CdSe-InP heterojunctions *(Invited Paper)*

Babak Nikoobakht, National Institute of Standards and Technology (United States)

No abstract available

9174-9, Session 3

Fabrication of GaN n-core/p-shell nanopillar arrays for optoelectronic applications

Albert V. Davydov, Sergiy Krylyuk, Ratan Debnath, Jong-Yoon Ha, Baomei Wen, Abhishek Motayed, National Institute of Standards and Technology (United States)

No abstract available

9174-10, Session 3

Vertical type GaN nanowire/thin film p-n junction light-emitting diodes *(Invited Paper)*

Young Joon Hong, Sejong Univ. (Korea, Republic of); Sung Jin An, Kumoh National Institute of Technology (Korea, Republic of)

For semiconductor nanowire-based optoelectronics, epitaxial nanowire arrays integrated on thin film offer ideal geometry for standard manufacturing and three-dimensional architectural devices. Meanwhile, the metal catalyst-assisted vapor–liquid–solid (VLS) process has produced well-controlled nanowire heterostructures promising for optoelectronic device applications. However, under some nanowire growth conditions, the method produces not only the desired nanowires but also nanocrystallites or film on substrates. In nanowire–thin film junction devices, such nanoislands and films can critically affect the junction device fabrication and performance.

The effect of nanoislands on nanowire–thin film junction light-emitting devices (LEDs) was examined by employing Ni-catalyzed VLS process that yields epitaxial GaN nanowire arrays and unnecessary nanoislands. Two different nanowire-based LED structures are prepared: n-nanowire/p-film (TYPE I); insulating layer-embedded coaxial p–n junction nanowires on n-film (TYPE II). TYPE I devices exhibited poor electrical rectifying features with a small on/off current and unclear turn-on threshold. The blue–green–yellow mixture electroluminescence resulted presumably from nanoislands. In contrast, TYPE II LEDs exhibited clear rectifying diode characteristics with typical EL turn-on voltage of ~3–4 V and enhanced on/off current ratio because the nanoisland layers were electrically isolated from p–n junctions by coating the crystallite layers with insulators. The EL color was pure blue from the depletion region of p-GaN shell layer. The LEDs were improved by suppressing the parasitic resistance and leakage current caused by the inevitable formation of nanoislands on the substrates during VLS nanowire growth.

9174-11, Session 3

Nanomaterials and nanostructures for LEDs: advanced nano-scale correlation of structural and optical properties of GaN nanorods *(Invited Paper)*

Frank Bertram, Otto-von-Guericke-Univ. Magdeburg (Germany)

In the past few years, tremendous progress has been achieved on epitaxial growth and processing of group III nitride nano- and microrods. Furthermore, these growth improvements have allowed the fabrication of optoelectronic devices based nanorods as active elements, i.e. light emitting diodes (LEDs). However, their efficiency is still far behind the performance of conventional GaN-based light emitting diodes.

The controlled growth of GaN nanorods offers a potential benefit for achieving higher efficiencies of III-Nitride based optoelectronic devices due to a high surface to volume ratio. Nanorods have a very large active area compared to their footprint. Since the active region is wrapped around the three-dimensional core (for core shell structures), the active layer scales with the rod's aspect ratio (i.e. the ratio of height and diameter). Therefore, by controlling their density, diameter and height, a tremendous increase of active surface can be achieved. Additionally, the low defect density in nanorods allows the characterization of single extended defects which is of high interest for a clear understanding of the formation of these defects.

In this study we present a direct nano-scale correlation of the optical properties with the actual real crystalline structure of single GaN nanorods using low temperature CL spectroscopy in a scanning transmission electron microscope (STEM). We concentrate on the crystalline quality, local In incorporation, n- and p-layer quality and defects of the complete structures.

9174-12, Session 3

P-type III-nitride nanowires: epitaxial growth, surface charge properties, and novel device applications *(Invited Paper)*

Zetian Mi, McGill Univ. (Canada)

No abstract available

9174-13, Session 3

Top-down III-nitride nanowires: from LEDs to lasers *(Invited Paper)*

George T. Wang, Qiming Li, Jeremy B. Wright, Sandia National Labs. (United States); Huiwen Xu, The Univ. of New Mexico (United States); Jonathan J. Wierer Jr., Daniel D. Koleske, Jeffrey J. Figiel, Sandia National Labs. (United States); Antonio Hurtado, Luke F. Lester, Changyi Li, Steven R. J. Brueck, The Univ. of

New Mexico (United States); Ting-Shan Luk, Igal Brener, Sandia National Labs. (United States)

Compared to conventional planar heterostructures, which dominate current optoelectronic architectures, III-nitride nanowires have several potential advantages including: reduced defect densities; reduced strain, which enables growth on arbitrary substrates as well as allowing for a greater range of alloy compositions and hence bandgap energies; access to nonpolar crystal faces; increased device area; and the ability to create 2-dimensional arrangements. I will discuss a "top-down" approach for fabricating ordered arrays of high quality III-nitride-based nanowires with controllable height, pitch and diameter. The process combines a lithographic dry etch followed by a selective, wet chemical etch of the nanowire sidewalls, leading to hexagonally-shaped nanowires with straight and smooth nonpolar m-plane sidewalls. Precisely engineered axial nanowire heterostructures can be formed from planar heterostructures, while radial nanowire heterostructures can be formed via regrowth. Using this top-down approach, both axial and radial type III-nitride InGaN/GaN nanowire LEDs were realized. The fabrication, structural characterization, and luminescence of these two different structures will be presented and their relative merits, weaknesses, and prospects discussed. III-nitride nanowires are also gaining interest as ultracompact and low-power nanoscale lasers in the UV-visible wavelengths. While GaN nanowire lasers typically operate in a multimode state, single-mode lasing is desired for applications needing high beam quality and spectral purity. Here we introduce multiple schemes for single optical mode selection and polarization control in GaN nanowire lasers, and demonstrate a photonic crystal nanowire laser design exhibiting a wide 60 nm of wavelength tuning.

9174-14, Session 3

Simulatenous optical and structural investigation of extended defects in nitride nanorods *(Invited Paper)*

Frank Bertram, Otto-von-Guericke-Univ. Magdeburg (Germany)

No abstract available

9174-15, Session 3

Bulk GaN and its application as substrates in building quantum nanostructures for some electronic and optoelectronic devices *(Invited Paper)*

Michal Bockowski, Institute of High Pressure Physics (Poland) and TopGaN Ltd. (Poland)

he use of GaN crystals grown by three methods (and their combinations): Hydride Vapor Phase Epitaxy (HVPE), high nitrogen pressure solution (HNPS) and ammonothermal method for optoelectronic (laser diodes) and electronic (transistors) devices will be presented. After a brief review on the historical development of the three crystallization methods, uniform and unique properties of GaN crystals which allow to use them as substrates for building devices will be shown. MOVPE and MBE growth of quantum nanostructures, their properties and then processing of devices will be demonstrated. Future challenges and perspectives will be discussed.

9174-16, Session 4

Van der Waals epitaxy of Bi_2Se_3 via hybrid physical-chemical vapor deposition for topological insulator applications *(Invited Paper)*

Joan M. Redwing, Joseph E. Brom, The Pennsylvania State Univ. (United States)

No abstract available

9174-17, Session 4

Growth of crystalline Al_2O_3 via low temperature thermal ALD: nanomaterial substrate phase stabilization *(Invited Paper)*

Sharka M. Prokes, U.S. Naval Research Lab. (United States); Michael Katz, NRC (United States); Mark E. Twigg, U.S. Naval Research Lab. (United States)

No abstract available

9174-18, Session 4

Aluminum titanium oxide films for optical encapsulation and broadband optical coupling

Juan J. Diaz Leon, Univ. of California, Santa Cruz (United States) and Nanostructured Energy Conversion Technology and Research (United States); Ernest Demaray, Demaray, LLC (United States) and Antropy, Inc. (United States); David M. Fryauf, Junce Zhang, Kate J. Norris, Univ. of California, Santa Cruz (United States) and Nanostructured Energy Conversion Technology and Research (United States); Mark Johnson, Tango Systems, Inc. (United States); Nobuhiko P. Kobayashi, Univ. of California, Santa Cruz (United States) and Nanostructured Energy Conversion Technology and Research (United States)

Efficient optical coupling for in-coming and out-going light is critical for optoelectronic devices such as solar cells and light emitting diodes. We developed a material system that acts both as a moisture barrier and as a broadband antireflective coating with very low optical absorption. We used pulsed DC reactive magnetron sputtering with AC substrate bias to deposit aluminum titanium oxide (AlTiOx) binary alloy thin films with different compositions. We studied physical properties of the films that underwent a high pressure moisture endurance test. Results suggest that there is a specific range of aluminum-titanium ratio where AlTiOx films withstand the endurance test while films with one type of cation or films with compositions out of the range fails. The ability to continuously change refractive index of pinhole-free AlTiOx films could ensure effective encapsulation and efficient optical in- and out- coupling will significantly benefit the design of optoelectronic devices.

9174-19, Session 5

Insights into enhanced MOF growth mechanisms on fibrous mats *(Invited Paper)*

Sarah D. Shepherd, RTI International (United States); Junjie Zhao, Mark D. Losego, Paul C. Lemaire, Philip S. Williams, Christopher J. Oldham, North Carolina State Univ. (United States); Howard

J. Walls, RTI International (United States); Gregory W. Peterson, U.S. Army Edgewood Chemical Biological Ctr. (United States); Gregory N. Parsons, North Carolina State Univ. (United States)

Metal-organic frameworks (MOFs) have significant potential for applications such as gas sorption, sensors, separation processes, catalysis, and storage. Our research is focused on controlling growth and attachment of MOFs on fibrous scaffolds to generate multifunctional materials utilizing ALD (atomic layer deposition) and other novel synthesis techniques. Integrated systems of MOFs on fibers should offer advantages in handling, safety, and development of new applications for these promising materials.

ALD as a nanoscale seeding layer for MOF growth greatly influences crystal structures achieved, growth mechanisms, and attachment. Employing Al2O3 and TiO2 ALD layers of varying thicknesses onto micro and nanofiber mats also has a significant impact on the properties of the MOF being formed. Uncoated mats were shown to have poorer attachment of MOF crystals, lower mass loading overall, and less uniform coverage of the fibers than ALD seeded mats. We will present results for synthesis of HKUST-1 MOF [Cu3(BTC)2] on fibers using solvothermal and layer-by-layer (LBL) techniques. MOFs produced on fibers can achieve dynamic loadings comparable to those of traditionally prepared MOF powders, significantly increasing the application potential for MOF-enabled devices. Insights into the dependence of crystal formation on synthesis technique, fiber size, and ALD layer will be discussed. Results given consider MOF crystal size, quality, attachment, and coverage of the fibrous substrate.

9174-20, Session 5

Molecule meets MOF: bridging the gap between organic and inorganic electronic materials *(Invited Paper)*

Mark D. Allendorf, A. Alec Talin, Michael E. Foster, Vitalie Stavila, François Léonard, Sandia National Labs. (United States)

Conventional inorganic electronic materials such as silicon achieve their outstanding electro-optical properties as a result of long-range crystalline order. However, these properties can only be tuned over a very limited range. In contrast, the properties of conducting organic polymers are readily modified, but the high degree of disorder in these materials leads to poor mobility. Metal-Organic Frameworks (MOFs) are a recently created class of supramolecular materials in which metal ions are coordinated to rigid organic “linker” molecules, creating a nanoporous structure with an exceptional degree of synthetic versatility. However, virtually all known MOFs are insulators as a result of the largely ionic nature of the metal-linker bonds. Recently, we discovered that infiltrating the pores of the copper-containing MOF HKUST-1 with redox-active guest molecules, such as TCNQ (7,7,8,8-tetracyanoquinododimethane), increases the electrical conductivity of thin film devices by as much as seven orders of magnitude. This emergent property results from a novel donor-bridge-acceptor geometry, in which TCNQ binds to two Cu(II) dimer units within the MOF pore. In this presentation we will describe the synthesis and characterization of Molecule@MOF materials. Coupling these results with first-principles electronic structure calculations demonstrates that conductivity occurs via a hopping mechanism facilitated by the bridging TCNQ. From these results it will be clear that Molecule@MOF represents a novel class of electronic materials with the potential to bridge the properties gap between inorganic and organic conductors, providing a high degree of electronic tailorability combined with long-range order for high charge mobility.

9174-21, Session 5

Organic-inorganic hybrid films using molecular-atomic layer deposition (MALD) *(Invited Paper)*

Jiyoung Kim, The Univ. of Texas at Dallas (United States)

No abstract available

9174-22, Session 6

Unconventional growth methods of indium phosphide nanowires on non-single crystal surfaces for thermoelectric devices

Kate J. Norris, Junce Zhang, David M. Fryauf, Juan J. Diaz Leon, Univ. of California, Santa Cruz (United States); Elane Coleman, Gary S. Tompa, Structured Materials Industries, Inc. (United States); Nobuhiko P. Kobayashi, Univ. of California, Santa Cruz (United States)

No abstract available

9174-23, Session 6

Magnetic doping of Ge-quantum dots: a growth study exploring the feasibility of modulating QD properties *(Invited Paper)*

Petra Reinke, Univ. of Virginia (United States)

No abstract available

9174-24, Session 6

GaAs-AlGaAs core-shell nanowire arrays: correlating MOVPE growth and luminescence properties *(Invited Paper)*

Paola Prete, Istituto per la Microelettronica e Microsistemi (Italy); Ilio Miccoli, Dept. of Engineering for Innovation, University of Salento, Lecce (Italy); Nico Lovergine, Univ. del Salento (Italy)

No abstract available

9174-25, Session 6

Fluctuations of the surface potential and photoconductivity in nanoheterostructures Si/Ge with SiGe nanoislands *(Invited Paper)*

Darina P. Storozhuk, Sergey V. Kondratenko, National Taras Shevchenko Univ. of Kyiv (Ukraine); Yuriy N. Kozyrev, Chuiko Institute of Surface Chemistry (Ukraine)

The electrical and optical properties of the Ge/Si heterostructures with Ge nanoislands grown by a molecular beam epitaxy (MBE) technique were investigated. To research the recombination processes spectral and time dependencies of lateral photoconductivity were studied. Photoconductivity at $T<190$ K, in the spectral region where c-Si is transparent, is attributed to interband optical transitions involving the states in the nanoislands. It is shown that when the temperature was decreased then the most significant is the decrease in the

photoconductivity of the fundamental absorption of the nanoislands. In the study of the kinetics of photoconductivity nanoheterostructure Si/Ge at T <120 K observed long-term relaxation of the photocurrent. Relaxation was more quick in case when only nanoislands were photoexcitatied. The obtained results has shown the high efficiency of recombination centers of electron-hole pairs in SiGe nanoislands. Spatial distribution of the surface potential of the heterostructure Ge-Si with nanoscale islands using the Kelvin probe method (KFM) were investigated. To study the local contact potential difference (CPD) of the system tip-surface atomic force microscopy with Sb-doped Au-coated conductive probes were used. The maximum value of CPD was observed at the location at the Ge nanoislands regions whereas the Si-surrounding exhibited the lowest value. The observed changes in the local surface potential due to the charge localized states in nanoislands and Ge-Si interface.

9174-26, Session 7

TiO_2 nanocrystal evolution in high-temperature atomic layer deposition and its application in solar energy harvesting *(Invited Paper)*

Xudong Wang, Univ. of Wisconsin-Madison (United States)

No abstract available

9174-27, Session 7

Nanoelectronic synaptic devices and materials for brain-inspired computational architectures *(Invited Paper)*

Rashmi Jha, The Univ. of Toledo (United States)

No abstract available

9174-28, Session 7

Investigation on resistive switching characteristics of ZnO thin film *(Invited Paper)*

Min Wei, Univ. of California, Santa Cruz (United States); Chunfu Li, Fan Yang, Hong Deng, Univ. of Electronic Science and Technology of China (China)

Recently resistive switching (RS) based on ZnO thin film has attracted considerable attention since ZnO with doping can improve the switching ratio and device performance. In this work, Cu/ZnO/AZO (Al-doped ZnO) and Cu/ZnCuO (Cu-doped ZnO) /AZO structures were fabricated for RS, using AZO as bottom electrodes due to its lattice matching with ZnO, and metal Cu was deposited as the top electrodes. The current–voltage (I–V) characteristics of these two structures are analyzed and compared. The results demonstrated that ZnCuO RS had a higher switching ratio and a larger range of setup and reset voltage than ZnO RS. In addition, we also found that the high resistance state (HRS) and the low resistance state (LRS) were accordance with space charge limited current effect (SCLC) and Ohm's law respectively.

9174-29, Session 7

Nano electronics with 2D layered semiconductors *(Invited Paper)*

Saptarshi Das, Argonne National Lab. (United States)

No abstract available

9174-30, Session 7

Continued development of dual-gated bilayer graphene devices *(Invited Paper)*

Stephen W. Howell, Thomas E. Beechem, Allister B. Hamilton, Taisuke Ohta, Khalid M. Hattar, Sandia National Labs. (United States)

No abstract available

9174-31, Session 7

Effect of interlayer orientation on electronic structure of 2D layered materials *(Invited Paper)*

Abbas Ebnonnasir, Univ. of California, Los Angeles (United States) and Colorado School of Mines (United States); Cristian V. Ciobanu, Colorado School of Mines (United States); Suneel Kodambaka, Univ. of California, Los Angeles (United States)

No abstract available

9174-32, Session 8

High-precision transfer-printing of vertically oriented 1D semiconductor arrays and integration into flexible devices

Mark Triplett, Univ. of California, Davis (United States); François Léonard, Sandia National Labs. (United States); M. Saif Islam, Univ. of California, Davis (United States)

Flexible electronics incorporating single crystalline semiconductors typically require post-growth processes to assemble the crystalline materials onto flexible substrates prior to device fabrication. We have developed a high precision transfer printing method for vertical arrays of single crystalline semiconductor materials which is adaptable to arrays with widely varying aspect ratios and densities enabling the assembly of arrays on flexible substrates in a vertical fashion. Subsequent fabrication processes for integrating transferred vertical arrays into flexible devices have also been developed and characterized. Flexible devices consisting of vertical silicon nano- and micro-wire arrays with robust top and bottom contacts have been fabricated and shown to be stable under bending stress, capable of reaching bending radii of 20mm. A thermionic-field emission current mechanism, due to the semiconductor-metal interfaces and doping levels present, was shown to be dominant for these devices. This mechanism is confirmed by device modeling and is consistent with standard semiconductor device physics principles, showing the consistency of our methods with current microelectronic fabrication techniques. The devices also act as flexible, deformable, nonpiezoelectric, and silicon based tactile sensors as they exhibit a reversible increase in conductivity with applied vertical stress. Our presented system provides a way forward for high-throughput, manufacturable, and scalable fabrication of flexible devices.

9174-33, Session 8

Carbon nanotube terahertz detector *(Invited Paper)*

Francois Leonard, Sandia National Labs. (United States)

We present a macroscopic terahertz detector based on optically thick films of dense and aligned carbon nanotubes. This p-n junction detector responds to a broad range of frequencies, shows a response at zero bias,

good linearity with THz power, and is intrinsically sensitive to polarization. A combination of electrical, thermal, opto-thermal, and thermoelectric experiments establishes the photothermoelectric mechanism of the response.

9174-34, Session 8

Acid-leached ?-MnO2 nanowires for electrochemical energy storage *(Invited Paper)*

Bryan Byles, Drexel Univ. (United States); Arunkumar Subramanian, Virginia Commonwealth Univ. (United States); Ekaterina Pomerantseva, Drexel Univ. (United States)

Nanowires of manganese oxides with tunnel crystal structures form a wide family of non-toxic and low cost materials with the general formula AxMnO2 (A = K, Na, Mg, etc.). These materials display a controlled variation in tunnel size and shape which can be used for a tunable ions intercalation. In addition, acid leaching of these phases opens ways to modify composition, morphology, electronic conductivity and surface properties of these materials, which are all crucial for the electrochemical intercalation-based energy storage. In this work we present electrochemical cycling of lithium ions in the original and acid-leached ?-MnO2 nanowires. We discuss the importance of the post-synthesis material treatment for the improvement of the functional properties. In addition, we demonstrate single nanowire electrochemical cells for the study of electrochemically-correlated mechanical properties of the nanowires.

9174-35, Session 8

Analyzing the evolution of microstructural disorder in thermally annealed bismuth telluride nanowires using a combined STEM/CBED approach *(Invited Paper)*

Kristopher J. Erickson, Steven J. Limmer, William G. Yelton, Caitlin Rochford, Michael P. Siegal, Douglas L. Medlin, Sandia National Labs. (United States)

Understanding microstructural disorder is critical for optimizing nanomaterials but poses a difficult challenge for characterization. The evolution of microstructural disorder within electrodeposited (ECD) Bi2Te3 nanowires, having thermoelectric applications, was studied following sequential ex situ thermal annealing steps using Convergent Beam Electron Diffraction and Scanning Transmission Electron Microscopy. This approach allowed changes in both intra-granular structural disorder and the grain structure to be quantified. These observations are put in context of the current understanding of ECD nanomaterial defect structures and ECD nanomaterial microstructure evolution during thermal annealing. This general approach is also applied towards quantifying structural changes in other nanomaterials.

9174-36, Session 8

SAD-GLAD core-shell nanorod arrays for fuel cell, photodetector, and solar cell electrode applications

Hilal Cansizoglu, Mehmet F. Cansizoglu, Mesut Yurukcu, Univ. of Arkansas at Little Rock (United States); Wisam J. Khudhayer, University of Babylon (Iraq); Nancy Kariuki, Deborah J. Myers, Argonne National Laboratory (United States); Ali U. Shaikh, Tansel Karabacak, Univ. of Arkansas at Little Rock (United States)

Shadowing effect in thin film growth originates from preferential deposition of obliquely incident atoms on higher surface points, which can lead to the formation of columnar thin films or isolated nanostructures. In a physical vapor deposition (PVD) technique, such as sputtering, one can control shadowing effect simply through substrate tilt angle. Glancing angle deposition (GLAD) technique, different than a conventional PVD process, incorporates a flux of atoms that are obliquely incident on a tilted and rotating substrate. Instead of a continuous thin film coating, these atoms can form arrays of three-dimensional nanostructures due to the shadowing effect. By simply controlling the deposition angle and substrate rotation speed, nanostructures of large variety of materials in the shapes of rods, screws, or springs can be obtained easily that are otherwise difficult to produce by conventional lithographical techniques. In this talk, a brief overview of the growth mechanisms and physical and optical properties of GLAD nanostructures will be presented. In addition, a new small angle deposition (SAD) technique as a simple means of conformally coating nanorod or nanowire arrays will be described. SAD utilizes a small tilt angle during PVD on nanostructured substrates, which allows the effective exposure of nanorod sidewalls to the incoming flux and leads to enhanced thin film conformality. In this talk, some recent results on core-shell nanorod arrays obtained by coating GLAD nanorods with a SAD shell will be presented. It will be shown that core-shell nanostructured geometries obtained by the simple SAD-GLAD method can significantly enhance catalyst activity for fuel cell electrodes, and charge carrier collection efficiency in photodetectors and photovoltaic solar cells.

9174-37, Session 8

Recombination-induced migration and reactions of hydrogen in SiC *(Invited Paper)*

Yaroslav Koshka, Mississippi State Univ. (United States)

No abstract available

9174-38, Session 9

Understanding and optimization of the sensitivity of nanoscale FET-based biosensors *(Invited Paper)*

Kaveh Shoorideh, Chi On Chui, Univ. of California, Los Angeles (United States)

No abstract available

9174-39, Session 9

Compound and alloyed contacts to Ge/Si and InGaAs nanowires and FinFETs *(Invited Paper)*

Shadi A. Dayeh, Univ. of California, San Diego (United States); Binh-Minh Nguyen, Los Alamos National Lab. (United States); Renjie Chen, Univ. of California, San Diego (United States); Wei Tang, Univ. of California, Los Angeles (United States)

The recent explosion of interest in alternative channel materials for sub-10 nm technology nodes urged studies of self-aligned ohmic compound and alloyed contacts to heterostructured Ge/Si core/shell nanowires and III-V semiconductor channels, similar to that of silicide contacts in the Si technology mainstream. We utilize in-situ transmission electron microscopy to unveil new observations on the detailed formation of such alloys and interfaces at an atomic scale by capturing single nucleation events during the reaction of Ni with Si, Ge and Ge/Si core/shell nanowires (NWs) and InGaAs FinFETs. The reaction between Ni and Ge/Si core/shell NWs is characterized with a single dominant Ni2Ge phase, in contrast to that of graded Ni fraction composition from Ni reservoir in a silicide/Si NW contact, and a Ni2Ge (111) //Ge (111) interface. We observe that the NiSix nucleates first and leads the reaction along the axis of the NW compared to Ni2Ge. Without appropriate management of this problem, it establishes a limit over which ultra-short channel devices in Ge/Si core/shell NWs could be realized. By removing the Si shell locally under the Ni contact to promote Ni2Ge formation, simultaneous propagation of the Ni2Ge and the NiSix was accomplished as demonstrated and was also demonstrated for a 2 nm Ge/Si gap in the heterostructured NW.

To study metal/III-V contact alloy formation, we utilized a novel wafer bonding technique to transfer thin (50 nm) InGaAs films onto SiO2/Si substrates and Si transmission electron microscopy (TEM) frames. InGaAs Fins with variable widths, lengths, and orientations were fabricated through a combination of electron-beam lithography and top-down dry etching steps, followed by Ni contact deposition. Rapid thermal annealing and in-situ TEM thermal heating cycles were conducted to react Ni with the InGaAs channel and deduce the reaction kinetics, dynamics, and resultant nickelide and interface structures. We observed sharp and abrupt nickelide-InGaAs interfaces for Fin channels narrower than 250 nm whereas multiple interfaces evolve for wider Fins. A faster reaction rate for [100] oriented Fins was observed when compared with [110] oriented ones. When a simple analytical treatment is applied to the Fin geometry, the nickelide length was found to have a square root dependence of inverse channel width and inverse channel height, in excellent agreement with experimental data. From this dependency, we extracted a surface diffusion coefficient of at a reaction temperature of 250 °C, which is 4-5 times larger than the extracted Fin 'body' diffusion coefficient. These results will be contrasted with those obtained for silicide/germanide reaction with Si/Ge nanowires, and the detailed structure, interface and reaction dynamics will be reported.

9174-40, Session 9

On-chip integrated 3D lithium ion batteries

Dmitry Ruzmetov, Andrei A. Kolmakov, Paul M. Haney, National Institute of Standards and Technology (United States); A. Alec Talin, Sandia National Labs. (United States)

All-solid-state Li-ion batteries are compatible with MEMS fabrication, exhibit extremely long lifetimes, negligible self-discharge rates, and offer enhanced safety. However, the low areal energy density of commercial thin film batteries limits both the performance and the miniaturization of autonomous MEMS. Simply increasing the thickness of the battery electrodes to store more energy reduces the power capability due to longer diffusion distances. In my presentation I will describe fabrication and performance of 3D Li ion batteries fabricated on Si and consisting of an array of cathode nanorods embedded in an anode matrix and separated by an ultra-thin solid electrolyte.

9174-41, Session 9

3D gate-all-around field effect transistors enabled by bridging nanowires

Jin Yong Oh, Univ. of California, Davis (United States); Hyun-June Jang, Won-Ju Cho, Kwangwoon Univ. (Korea, Republic of); Jong-Tae Park, Univ. of Incheon (Korea, Republic of); M. Saif Islam, Univ. of California, Davis (United States)

Transistors enabled by one-dimensional nanowires have attracted attention because they are expected to present a pathway to overcome the roadblocks to Moore's law and can enable gate-all-around transistors. However, lack of reproducibility in their growth, alignment into arrays, and contact formation to enable scalable fabrication of transistors is challenging. In this presentation, we demonstrate the integration of gate-all-around field-effect-transistors based on horizontally aligned silicon nano-bridges without experiencing tedious post-growth processes. These nano-bridge gate-all-around transistors exhibited a high on/off-current ratio, low sub-threshold swing and very low off-currents. In addition to designing low-voltage non-volatile memory cells, the photosensitivity of the 3D FETs is employed to demonstrate several analog and digital applications such as electro-optical OR gate circuit elements and frequency doublers.

9175-301, Session Plen

CPV: Lessons from the First 100MW and the Explosion of Next Generation Technologies

Adam P. Plesniak, Arzon Solar, LLC (United States)

The past decade has seen concentrator photovoltaics (CPV) technology transition from a few backyard experiments to an installed global capacity of well over 100 MW. With several utility scale power plants in commercial operation, the presentation will first focus on history and quality of performance since commissioning and overall customer satisfaction. Critical lessons learned from the process of designing, manufacturing and installing product for the utility scale renewable generation market are discussed. The presentation will reflect on how lessons thus far will guide CPV innovators through the flowering of Next Generation CPV technologies, from spectrum splitting optics to five junction solar cells, currently underway throughout the industry. Overall, CPV continues to serve as a robust platform for the new ideas and research needed to mature the higher performance and lower cost technologies critical for continued competitiveness of CPV in the renewable generation marketplace.

9175-2, Session 1

300 sun light engine for high concentrator application studies

John H. Park, Richard Jarzebiak, John Degroff, Katy Zadrovicz, Anderson Chen, Oriel® Instruments, a Newport Corp. Brand (United States)

As renewable energy generation is gaining momentum, it is clear that high powered turnkey sources specifically designed to simulate solar concentrator conditions will be needed to assist in evaluating receiver performances in a controlled environment. To fulfill this need, a solar simulator capable of producing 300 suns over a 1cm square area was demonstrated. For this task, an Oriel Instruments Solar Simulator chassis was selected using a 1.6kW Xe bulb. A concentrator tube was designed concentrate the collected Xe emission into a 1cm by 1cm beam spot at a working distance of 44mm. A proprietary filter was used to spectrally match the system to IEC and ASTM AM1.5D specifications. A spectrally flat Newport thermopile detector 818P-100-55 coupled with various apertures was used in a time transient metrology to empirically determine the unit is producing 300 suns with 12% beam uniformity at the 44mm working distance. With this light engine, large area high powered concentrator research can be used to easily and rapidly simulate concentrated applications.

9175-3, Session 1

Rugate fibers for solar concentration

Esmaeil Hooman Banaei, Apurva Jain, Hesam E. Arabi, Flex Optronix Technologies, LLC (United States); Amador Menéndez-Velázquez, ITMA Materials Technology (Spain)

Rugate filters, having smooth periodic refractive index variation across the thickness, have been used for several types of solar concentrator systems. Most commonly employed in spectrum-splitting solar concentrator systems, these filters efficiently split the solar spectrum into multiple wavelength ranges for conversion with an optimized bandgap-matched photovoltaic cell. Rugate filters have been also suggested as a top layer for luminescent solar concentrators (LSCs) to minimize waveguide surface losses of fluoresced light while allowing the incident solar spectrum to efficiently enter the waveguide. With current fabrication technology, rugate filters are expensive, and limited to small sizes and flat geometry.

We have developed an innovative and low-cost manufacturing process for fabrication of large-area rugate filters that can conform to any shape. Here, we will present simulation results on two solar concentration applications using our novel rugate filters in fiber geometry (i.e., rugate fibers): 1) Circularly symmetric polymer fiber luminescent solar concentrators (LSC) with rugate filter structures optimized for its fluorescence spectrum fabricated around its outer surface. This approach approximately doubles the concentration efficiency of fiber LSCs compared to the state-of-the-art. 2) Hollow-core fibers with rugate filter structures fabricated around the core with ultra-broadband reflection spectrum that essentially covers the entire solar spectrum. We introduce the use of such hollow-core rugate fiber bundles as a highly efficient light-guide medium for delivering broadband concentrated sunlight for internal lighting, direct heating and hydrogen generation applications.

Finally, we will present our progress towards experimental realization of both classes of rugate fibers.

9175-4, Session 1

Freeform solar concentrator with a highly asymmetric acceptance cone

Brian M. Wheelwright, College of Optical Sciences, The Univ. of Arizona (United States); J. Roger P. Angel, The Univ. of Arizona (United States); Blake M. Coughenour, Kimberly N. Hammer, College of Optical Sciences, The Univ. of Arizona (United States)

A solar concentrator with a highly asymmetric acceptance cone is investigated. Concentrating photovoltaic systems require dual-axis sun tracking to maintain nominal concentration throughout the day. In addition to collecting direct rays from the solar disk, which subtends ~0.5°, concentrating optics must allow for in-field tracking errors due to mechanical misalignment of the module, wind loading, and control loop biases. The angular range over which the module maintains 90% of nominal output is defined as the acceptance angle. Concentrators with substantial rotational symmetry likewise exhibit rotationally symmetric acceptance angles. In the field, this is a poor match with azimuth-elevation trackers, which have inherently asymmetric tracking performance. Pedestal-mounted trackers with low torsional stiffness about the vertical axis have better elevation tracking than azimuthal tracking. Conversely, trackers which rotate on large-footprint circular tracks are limited by elevation tracking performance. Guaranteeing symmetric tracking performance increases tracker costs.

We show that a line-focus concentrator, composed of a parabolic trough primary reflector and freeform refractive secondary, can be tailored to have a highly asymmetric acceptance angle. When mounted on a tracker with poor performance in the direction of largest acceptance angle, the combination performs better than a rotationally-symmetric system of the same geometric concentration. In the design given, the azimuthal acceptance angle is +/-1.15°, while the elevation acceptance angle is only +/-0.35°. This is well-suited for a pedestal alt-azimuth tracker with a low cost slew bearing (without anti-backlash features).

9175-6, Session 2

A small-scale concentrating solar thermal system

Christi K. Madsen, Texas A&M Univ. (United States); Alan Schulz, Wei Wu, aldo sosa, Texas A&M University (United States); Ran Huang, Texas A&M Univ. (United States); Tasnim Mohamed, Robert Atkins, John Simcik, Texas A&M University (United States)

The design, fabrication and characterization of a small-scale concentrating solar thermal system will be presented. The first application is to address residential hot water needs; however, additional applications can be enabled with the system's greater efficiency and temperature range compared to evacuated tube and flat plate systems. A large Fresnel lens, with an area on the order of one square meter on a two-axis tracking mount, is used to concentrate the solar energy and focus it to an area of a few square centimeters. A new solar receiver design will be discussed which leverages the thermal loss management properties of evacuated tubes in addition to efficient heat transfer to a fluid. Optical testing of the Fresnel lens and tracking mount concentration and efficiency as well as thermal stagnation and dynamic test results will be presented, demonstrating the overall efficiency of the system. The system is unique compared to currently available commercial domestic hot water systems, by leveraging concentration to achieve the maximum solar-to-thermal energy efficiency and low cost.

9175-7, Session 2

Design and laboratory tests of a prototype molten salt receiver for linear Fresnel CSP

Philip Gleckman, AREVA Solar, Inc. (United States)

AREVA Solar has constructed a prototype linear Fresnel power plant module that uses molten salt as the heat transfer fluid. This prototype represents a new technology option that joins parabolic troughs and towers that use molten salt for heat transfer and storage. The prototype dimensions are full commercial scale except for the length which is limited by available land and cooling equipment at Sandia National Laboratory's Molten Salt Test Loop facility.

The demonstration uses the same reflector field components as those deployed at AREVA Solar's 125 MWe commercial plant in India. The novel component is the receiver which has been designed for compatibility with the same reflector field. This receiver uses an array of heat collector elements rated for operation with 550°C salt. Light is collected from the field to the absorbing surfaces by mirrors in the receiver.

The demonstration was built mainly to validate the modeled thermal efficiency of the receiver, defined as the fluid enthalpy rise relative to the heat input. We will describe the experimental design, which includes an accurate measurement of optical flux on an unprecedented scale (1x100m). An axially nonuniform flux is expected, which is an artifact of the relatively short (50 m) length of the test reflector field compared to the receiver height (30 m). We describe how the experiment takes this artifact into account so that the results faithfully represent what one would expect at commercial length. We present optical and thermal models of the demonstration, and laboratory test results of critical components.

9175-8, Session 2

Reduction of radiative heat losses for solar thermal receivers

Clifford K. Ho, Joshua M. Christian, Jesus Ortega, Julius Yellowhair, Sandia National Labs. (United States); Matthew J. Mosquera, Charles E. Andraka, Sandia National Laboratories (United States)

Conventional receivers for concentrating solar power consist of panels of tubes with heat transfer fluid that absorb concentrated sunlight. The panels are arranged facing the incoming solar irradiance, but traditional cylindrical or cubical designs also maximize radiative and convective heat losses to the environment. This paper presents novel STAR (Solar Thermal Advanced Receiver) designs employing radial and finned tube configurations at multiple scales that reduce the radiative view factors and heat loss. In addition, the STAR designs have a trapping effect on the incident solar radiation, increasing the absorbed solar energy and receiver efficiency.

Parametric studies using computational fluid dynamics models coupled to optical ray tracing tools have been performed to evaluate the view factor, radiative and convective heat loss, and thermal efficiency of different STAR patterns relative to conventional designs. Both meso- (millimeters to centimeters) and macro-scale (meters) simulations have been performed to evaluate the impact of these features and processes at multiple scales, from individual tubes to the entire receiver. Results show that the new STAR designs can reduce radiative view factors by 70% and overall heat loss by 50% with an increase in thermal efficiency of 10% relative to conventional designs. This paper presents a summary of the designs, modeling results, issues, and proposed testing.

9175-9, Session 3

Plasmonic nanoparticle based spectral fluid filters for concentrating PV/T collectors

Drew DeJarnette, Todd Otanicar, Nick Brekke, Parameswar Hari, Kenneth Roberts, The Univ. of Tulsa (United States); Aaron E. Saunders, nanoComposix, Inc. (United States); Ratson Morad, Cogenra Solar, Inc. (United States)

Advanced solar conversion systems will require technologies that are capable of efficiently converting solar energy across the whole spectrum in an affordable manner while efficiently providing electricity and dispatchable thermal energy. An attractive method for this is by coupling photovoltaic cells to a thermal energy collector. These systems are often limited by the degradation of PV at high temperatures or the low conversion efficiency of thermal energy to electricity at low temperatures. A potential way to overcome this limitation and operate at higher temperatures is through the use of spectral filtering. Here we propose a design for a new type of concentrating PV/T collector to utilize plasmonic nanoparticles directly suspended in the working fluid of the thermal engine to filter the incoming solar flux. This liquid filter serves two purposes: the direct capture of thermal energy as well as filtering off of key portions of the spectrum before transmission to the PV cell. Our device builds upon the current Cogenra T14 system with a two-pass architecture: the first pass on the back side of the PV cell pre-heating the fluid from any thermalization losses, and the second pass in front of the PV cell to achieve the spectral filtering. Of primary interest here are the design choices surrounding the proper suite of nanoparticles to achieve high levels of sub-gap absorption while maximizing facile synthesis and minimizing cost. Additionally some preliminary modeling on the necessary thermal management of the two pass configuration is reported.

9175-10, Session 3

Sun to fibers (S2F): massively scalable collection and transmission of concentrated solar light for efficient energy conversion and storage

Juan Jose Diaz Leon, Univ. of California, Santa Cruz (United States) and Nanostructured Energy Conversion Technology and Research (United States); Matthew P Garrett, Junce Zhang, Baskin School of Engineering (United States) and Nanostructured Energy Conversion Technology And Research (NECTAR) (United States); Katherine Han, Antropy Inc. & Demaray LLC (United States); Ernest Demaray, Antropy Inc. (United States) and Demaray, LLC (United States); Roger W. Anderson, Univ. of California, Santa Cruz (United States); Allan Lewandowski, Allan Lewandowski Solar Consulting, LLC (United States); William Bottenberg, Bottenberg Associates (United States); Nobuhiko P. Kobayashi, Univ. of California, Santa Cruz (United States) and Nanostructured Energy Conversion Technology and Research (United States)

Concentrated solar energy has proven to be an efficient approach for both solar thermal energy applications and photovoltaics. Here, we propose a passive optical device, the adiabatic optical coupler (AOC), that efficiently couples concentrated solar light from a primary solar concentrator into an optical fiber, enabling light collection and energy conversion/storage to be at two different locations connected via low loss transmission, maximizing the overall system efficiency. The AOC offers secondary concentration of concentrated solar light through an adiabatic optical mode conversion process. Solar light highly concentrated by the two stage concentrator is delivered with very high exergy at the end of the optical fiber to be subsequently energy-converted or thermally stored. The ability to transport this high energy flux as light eliminates the need for high temperature working fluids replacing them with an optical fiber. In order to design the AOC and related peripherals, we used various modeling tools to cover different optical regimes at macroscopic and microscopic scales. We demonstrated a set of optical thin films with spatially varied refractive index up to 3 and negligible optical absorption by using a proprietary sputtering technique to fabricate the AOC. We further studied the films using experimental measurements and theoretical analysis to optimize their optical properties. Preliminary cost analysis suggests that solar thermal power generation systems that employ our S2F concept could offer cost and efficiency required for us to achieve the 2020 SunShot initiative levelized cost of electricity (LCOE) target. Success of this endeavor could change the energy conversion paradigm, and allow massively scalable concentrated solar energy utilization.

9175-11, Session 3

Shaping solar concentrator mirrors by radiative heating

J. Roger P. Angel, Thomas E. Stalcup Jr., The Univ. of Arizona (United States) and REhnu, Inc. (United States); Brian M. Wheelwright, Stephen H. Warner, Kimberly N. Hammer, The Univ. of Arizona (United States)

The University of Arizona has built and tested a process to rapidly mold glass reflectors by radiative heating. The new shaping method allows for production of reflectors with both line-focus, as widely used CSP plants, and point-focus. The shaped glass is coated with silver to obtain self-supporting, second surface glass mirrors, proven in in trough plants to have 20-year longevity. In the manufacturing process, a float glass square 1.65 m on a side is softened and slumps under gravity into a full-body mold. To preserve the original high polish of the float glass on both front and back surfaces, as required for a second surface mirror, the mold surface is machined to the required shape as grooves which intersect at cusps, reducing the mold contact area fraction to << 1%. The mold surface is gold-plated so as not to absorb thermal radiation. The shaping cycle starts with rigid glass at 500C. Rapid heating is provided by nichrome ribbon elements heated to 900C, in a 350 kW power burst. After two minutes, the slumped glass conforms accurately to the mold shape. It is then cooled back to the rigid state by a combination of radiation and forced convection, with a targeted time for the full cycle of 200 seconds. The shape of the replicas is measured by reflection of parallel laser beams on a one-inch square grid. Slope values are measured at 4000 points on a one inch grid, with a targeted replica accuracy of 1 mrad rms.

9175-12, Session 3

Self-tracking phase change concentrator device demonstrator

Volker Zagolla, Eric J. Tremblay, Christophe Moser, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Concentration photovoltaic systems uses free-space optics to concentrate sunlight onto photovoltaic cells, using mechanical trackers to accurately track the sun's position and keep the focal spot on the PV cell. We recently proposed and demonstrated a proof-of concept of a self-tracking mechanism using a phase-change material to greatly extend the acceptance angle of the concentration device. The light responsive mechanism allows for efficient waveguide coupling and light concentration independent of the angle of incidence inside its angular range of acceptance. The system uses a lens pair to achieve a flat Petzval field curvature over the acceptance angle range. A waveguide slab acts as the concentrating device. The use of a dichroic prism membrane separates the solar spectrum into two parts, lower wavelengths (<750nm) are coupled into the waveguide, while the energy of higher wavelengths (>750nm) is used to power the self-tracking mechanism. The energy in this part of the spectrum is absorbed by a carbon black paraffin wax mixture that undergoes a phase change and subsequently creates a coupling feature due to thermal expansion which allows the lower wavelength part to be coupled into the waveguide.
We show the extension of our proof-of concept to a device-like demonstrator, featuring the extension to a lens array and much larger dimensions. The demonstration device has a 50x concentration factor and an acceptance angle of +/- 16 degrees. We present experimental and simulation results of the demonstration device, fully characterizing its components and performance. A roadmap to higher concentration factors outlines future work.

9175-13, Session 4

Ray trace optimization of light trapping filtered concentrator

John Lloyd, Emily D. Kosten, Emily C. Warmann, Harry A. Atwater Jr., California Institute of Technology (United States)

Decades of research and development of monolithic multijunction solar cells has achieved high efficiencies, but despite continuing development, the obstacles of current and lattice matching still present challenges. Spectrum splitting is an alternative approach where optical components, rather than the semiconductor devices themselves, direct different energy light to the appropriate bandgap photovoltaic device.

Our approach is a type of cavity concentrator, where a textured dielectric slab with angle restricting elements randomizes and traps incident light while aperiodic dielectric multilayer filters designed for omnidirectionality selectively admit light into photovoltaic devices with appropriately tuned bandgaps. Previous work on this design involved a statistical ray optics multipass model coupled with modified detailed balance calculations. Here, we extend the analysis to include a full ray trace model of the design. The scripted model allowed for rapid optimization of the geometric design parameters as well as incorporation of non-idealities that were absent from the multipass model. Furthermore, this approach allowed for evaluation of multiple candidate filter sets, with the design optimized in the ray trace for each set of filters. We achieve module efficiencies in the range of 35-40% for attainable materials and filters.

9175-14, Session 4

Diffractive spectrum splitting module using high-contrast gratings *(Invited Paper)*

Sunita Darbe, Emily C. Warmann, Harry A. Atwater Jr., California Institute of Technology (United States)

Traditional multijunction solar cells have complexities and limitations due to series electrical connection, lattice-matching requirements and the need for tunnel junctions. Alternate multijunctions geometries employing spectrum-splitting optics to orient each frequency band of light toward a solar absorber that can best convert it are an attractive option to address some of these limits. Such devices can incorporate many independently connected cells with more freely optimized bandgaps.

We explore high-contrast gratings (HCG) as spectrum-splitting optics. In these gratings, constructive or destructive interference between incident light and the guided-mode within the high refractive-index planar diffractive structure result in very high reflectivity or transmissivity,

respectively. Appropriately designed HCG can be broadband and polarization insensitive. GaP and TiO2 structures embedded in glass, polymer or other low-index material are modeled using rigorous coupled-wave analysis (RCWA). Design rules-of-thumb are developed. RCWA and modified detailed balance calculations are used in conjunction to give an estimate of system efficiency accounting for realistic losses. HCG performance is compared with dielectric multilayer stacks and holograms as alternative methods for spectral splitting.

Mid-to-high concentration and six to eight III-V materials as absorbers for subcells lattice-matched to GaAs or InP substrates give the potential for module efficiencies well in excess of current world records.

9175-15, Session 4

Positional irradiance measurement: characterization of spectrum-splitting and concentrating optics for photovoltaics

Cristofer A. Flowers, Sunita Darbe, Carissa N. Eisler, California Institute of Technology (United States); Junwen He, Univ. of Illinois at Urbana-Champaign (United States); Harry A. Atwater Jr., California Institute of Technology (United States)

Multijunction photovoltaics enable significantly improved efficiency over their single junction analogues by mitigating unabsorbed sub-bandgap photons and voltage loss to carrier thermalization. Lateral spectrum-splitting configurations promise further increased efficiency through relaxation of the lattice- and current-matching requirements of monolithic stacks, albeit at the cost of increased optical complexity. Consequently, in order to achieve an effective spectrum-splitting photovoltaic configuration it is essential that all optical losses and photon misallocation be characterized and subsequently minimized.

We have developed a characterization system that enables us to map the spatial, spectral, and angular distribution of illumination incident on the subcell reception plane or emerging from any subset of the concentrating and splitting optics. This positional irradiance measurement system (PIMS) comprises four motorized stages assembled in a Z-X-R-Y configuration with three linear degrees of freedom and one rotational degree of freedom, on which we mount an optical fiber connected to a set of spectrometers covering the solar spectrum from 280-1700 nm. In combination with a xenon arc lamp solar simulator with a divergence half angle of 1.3 degrees, we are able to characterize our optics across the full spectrum of our photovoltaic subcells with close agreement to outdoor conditions. We have used this tool to spectrally characterize holographic diffraction efficiency versus diffraction angle; multilayer dielectric filter transmission and reflection efficiency versus filter incidence angle; and aspheric lens chromatic aberration versus optic-to-receiver separation distance. These examples illustrate the versatility of the PIMS in characterizing optical performance relevant to both spectrum-splitting and traditional multijunction photovoltaics.

9175-16, Session 5

Design of folded holographic spectrum-splitting photovoltaic systems for direct and diffused illumination conditions

Yuechen Wu, Juan M. Russo, The Univ. of Arizona (United States); Shelby D. Vorndran, College of Optical Sciences, The Univ. of Arizona (United States); Raymond K. Kostuk, The Univ. of Arizona (United States) and College of Optical Sciences, The Univ. of Arizona (United States)

Spectrum-splitting is a beneficial technique to increase the efficiency and reduce the cost of photovoltaic systems. This technique divides the incident solar spectrum into spectral components that are spatially separated and directed to PV cells with matching spectral responsivity characteristics. This approach eliminates problems associated with current and lattice matching that must be maintained in tandem multi-junction systems. In this paper, a two-junction holographic spectrum-splitting photovoltaic system is demonstrated with a folded PV geometry. The system is designed to make better use of both direct and diffused solar irradiation. It consists of holographic elements, a wedge-shaped optical guide, and PV substrates with back reflectors. The holographic elements associated with back reflectors spatially split the solar spectrum into corresponding PV substrates, and the wedge-shaped optical guide traps the diffuse rays inside the system until they are absorbed by the cells. In this paper, the system is analyzed under direct illumination for an InGaP2/GaAs combination, and an experiment is set up to measure the optical efficiency of holographic elements combined with the wedge substrate for the PV cells. A system efficiency of 34.46% is computed with data from an experimental reflection hologram. Also, a non-sequential ray tracing model is used to simulate the optical performance under direct, diffuse and global irradiation conditions. The optical and system efficiency, as well as the improvement over best bandgap (IoBB) PV cell also evaluated based on the simulation results.

9175-17, Session 5

Analysis of dispersive spectrum splitting systems

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Shockley and Queisser have shown that systems based on single junction PV cells are limited to a system efficiency of 33%. This restriction results from the mismatch between the photon energy of the incident sunlight and the inability of a single junction device to optimally convert the broad incident spectrum. One approach to overcome this difficulty is to incorporate multiple PV cells with different bandgaps that are optimized to convert different parts of the incident spectrum to electrical power. Spectrum splitting configurations distribute incident photons onto several single bandgap PV cells that are spatially separated. Although, systems with different methods and geometries have been proposed, optical systems relying on reflective filters have not been compared to transmissive ones. Since reflection-type films are primarily based on the interference of reflected waves from optical interfaces, systems based on these filters do not have dispersion losses. Dispersive spectrum splitting systems rely on optical elements that use diffraction or refraction for spectral separation. The dispersion from a single broad band optical element can be used for spectral separation. The geometrical relationship between focusing power, the degree of dispersion, the system aperture, and the PV cell aperture and position can be used to tailor the spectral shape of the incident spectrum into each of the PV cells comprising the system. In this paper, the effects of dispersion introduced by transmission type filters are presented compared to reflective filters.

9175-18, Session 5

Two-axis spectral splitting optical concentrator based on single injection molded plastic element

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High efficiency concentrator photovoltaic systems are currently based on III/V cells and, to offset the high cell capital cost, elevated optical concentrations are used, with consequent reduction in acceptance angles and tight tolerance optics.

While this allows for spectacular conversion efficiencies, it does not provide cost effectiveness in a market dominated by low efficiency/low cost technologies.

An alternative approach, well known in literature, is based on the combined use of an optical concentrator and a spectral splitting element allowing for the use of separate cells with different spectral responses and, thus, opening the way to a much wider range of possible materials and technologies.

While many configurations have been presented during the years, optical efficiency has often been an issue due to the separate action of the concentrating and splitting element.

We propose here, as substantial evolution of a previous design [1], a single injection molded plastic non-imaging optical element embodying both two axis concentration and spectral splitting functions. Based on the specific dispersion characteristics of polycarbonate and on a constructive analytical design procedure, this element allows for optical efficiencies exceeding 80%. Theory, simulations and preliminary experimental results will be presented.

1. M. Stefancich, A. Zayan, M. Chiesa, S. Rampino, D. Roncati, L. Kimerling, and J. Michel, "Single element spectral splitting solar concentrator for multiple cells CPV system," Optics Express 20, 9004-9018 (2012).

9175-19, Session 6

Low cost anti-soiling coatings for CSP collector mirrors and heliostats

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Most concentrating solar power (CSP) facilities in the USA are located in the desert southwest of the country where land and sunshine are abundant. But one of the significant maintenance problems and cost associated with operating CSP facilities in this region is the accumulation of dust, sand and other pollutants on the collector mirrors and heliostats. The optical performance of the CSP collectors is key to achieving low electricity costs, where a 1% decrease in reflectance directly leads to a 1% increase in the levelized cost of electricity (LCOE) generated by these facilities.

In this paper we describe the development of low cost, easy to apply anti-soiling coatings based on superhydrophobic (SH) functionalized nano silica materials and polymer binders that posses the key requirements necessary to inhibit particulate deposition on and sticking to CSP mirror surfaces, and thereby significantly reducing mirror cleaning costs and facility downtime. These requirements are excellent optical clarity with minimal diffuse reflectance, coating mechanical and exposure durability in harsh desert environments while maintaining SH and dirt shedding properties. The coatings developed to date have excellent SH properties with water contact angles > 1650 and rolling angles < 50. The solar weighted optical transmission of the anti-soiling coating over the 250 nm to 3?m is >99% of uncoated mirror surfaces with coating diffuse reflectance being <1% over this wavelength range. Ongoing mechanical and accelerated solar UVA exposures also indicate these coatings will meet the required durability goals.

9175-20, Session 6

Optical and adhesive properties of dust deposits on solar mirrors and their effects on specular reflectivity and electrodynamic cleaning of solar collectors for mitigating energy-yield loss

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Operating CSP plants with high specular reflection efficiency with minimum thermal losses determines the overall system performance in $/kWh. Utility-scale solar power plants are mostly installed in deserts and semi-arid zones of the world where large areas having highest direct normal irradiance with minimal interruption by rain or clouds are available. In these areas, dust layer buildup on solar collectors becomes a major cause for energy yield loss. Development of transparent electrodynamic screens (EDS) and their applications for self-cleaning operation of solar collectors are presented. An EDS consists of thin rectangular, transparent conducting parallel electrodes deposited on a dielectric surface. The electrodes are insulated from each other and are embedded within a thin transparent dielectric layer. The electrodes are activated using three-phase high-voltage pulses at low current (< 1 mA/m2). The three-phase electric field lifts the dust particles form the substrate by the electrodynamic forces and a traveling wave that propels the dust layer off of the collector's surface. The cleaning process takes less than 2 minutes; requires less than 1 Wh/m2 energy without any water or manual labor. The reflection efficiency can be restored > 95% of the original clean-mirror efficiency. We briefly review (1) loss of specular reflection efficiency as a function of particle size distribution and dust composition, (2) degradation of mirrors caused by dust deposits at high RH, and (3) the effects of the electrode design and materials used on the EDS-integrated solar mirrors. The electrode geometry and material selection are researched in order to produce the best optical and electrical performance including the cost-effective deposition techniques. Finally, the essential features of levelized cost of mirror cleaning (LCOMC) by EDS are presented.

9175-21, Session 6

Anti-oxidation, high-performance solution-processed Ni plasmonic nanochain-SiOx selective solar thermal absorbers

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In order to address the metal oxidation issue in cermet solar thermal absorbers at high working temperatures, we developed solution-processed plasmonic Ni nanochain-SiOx ($x \leq 2$) selective solar thermal absorbers that exhibit high solar absorption, low thermal emittance, and strong anti-oxidation behavior up to 600 ºC in air. The thermal stability is far superior to more conventional Ni nanoparticle-Al2O3 selective solar thermal absorbers, which readily oxidize at 450 ºC. Ni nanochains were embedded in SiOx and SiO2 matrices which are derived from hydrogen silsesquioxane (HSQ) and tetraethyl orthosilicate (TEOS) precursors, respectively. Fourier transform infrared spectroscopy (FTIR) shows that the dissociation of Si-O cage-like structures into Si-O networks helped to retard the oxidation process of Ni, possibly by facilitating the formation of chemical bonding between Si in the matrix and the Ni nanochains. X-ray photoelectron spectroscopy (XPS) further shows that the excess Si from the dissociation of HSQ formed silicide-like chemical bonds with Ni that are robust to high temperature oxidation and protect the Ni nanostructures. Moreover, the Ni-SiOx system showed 90% solar absorptance and a low thermal emissivity of 15% at 300 ºC in air, compared to ~30% emittance of conventional coatings at this temperature. This technology helps to eliminate the problem of vacuum breaching and further reduces the fabrication cost of the solar selective coating. With a high solar absorptance, a low thermal emittance, and excellent anti-oxidation property, this type of selective solar thermal absorber can potentially lead to transformative technologies such as vacuum-free CSP receivers.

9175-22, Session 6

The end of the road for carbon-based metal oxide matrices for selective solar absorbers?

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A novel solar absorber coating based on a nanocomposite of carbon in nickel oxide on an aluminium substrate was developed. The material was found to have the optical properties required of an ideal solar absorber: high absorbance in the solar wavelength range and low emittance at infrared wavelengths. However, lifetime testing of the material gave poor results. The reason for this was therefore investigated. TGA-FTIR analyses showed mass loss of the solar absorber material during extended heating thereof in air, and further proved that carbon dioxide was released leading to loss of carbon. The SEM EDS analyses of the thin film on the aluminium substrate showed that carbon was not confined to the pores of the material, but appeared to rather be evenly distributed throughout it. The carbon signal which had been evident when an area EDS analysis was performed on a pre-lifetime test sample was not present in a similar analysis of a post-lifetime sample, which again indicated loss of carbon from the material upon heating in air. The stability of the solar absorber material, specifically with respect to the carbon content, needs to be enhanced in order for it to find use as a solar absorber, although the improvements achieved may not be sufficient to allow the material to pass the required lifetime tests.

9175-23, Session 7

First demonstration of a novel 2D-waveguiding solar concentrator

Ran Huang, Yuxiao Liu, Christi K. Madsen, Texas A&M Univ. (United States)

The first experimental demonstration results will be presented for a novel, two-dimensional waveguiding solar concentrator consisting of a primary concentrator (a microlens array) and a secondary concentrator (tapered multimode waveguides) coupled to photovoltaic cells. The microlens array collects the incident sun light and focuses it onto a turning mirror. The turning mirror couples the light into a tapered multimode waveguide, which alleviates connection, cooling and uniformity issues associated with conventional solar concentrating systems. Therefore, a large area of light can be efficiently concentrated to a small waveguide cross-section and guided to an array of co-located photovoltaic cells with high optical efficiency. To achieve the maximum coupling efficiency of the light to the waveguide, the design of the turning mirror and waveguides are optimized to avoid any inherent decoupling loss in the subsequent waveguide propagation. Simulations indicate that the structure, using only total internal reflection surfaces, can achieve 800x concentration with 89% optical efficiency under ±0.7 ? incidence angle. We will present details on the experimental device characterization. A critical requirement for this design is maintaining low waveguide propagation losses, which we demonstrate can be less than 0.2 dB/cm.

9175-24, Session 7

Field performance of CPV systems using different Fresnel lenses

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Concentrator photovoltaic (CPV) arrays utilize mirrors or refractive lenses to concentrate sunlight (typically >500 suns) onto high-efficiency multijunction solar cells. In the last several years, refractive Fresnel lenses have become dominant among CPV companies as the method of light collection. Two types of Fresnel lenses are currently used in the industry: PMMA (polymethyl methacrylate) and SOG (silicone on glass). There are currently several vendors for each type of lens. Differences in fabrication and tooling can cause the same type of lens from different vendors to exhibit different performance characteristics. In order to optimize the energy output of a CPV system, it is important to understand lens performance in the field. However, there is very limited data on the comparison of lenses from different vendors in real world conditions. Due to the wide variation of weather with location and time, it is necessary to do such a comparison in the same location using the exact same configurations. The 30MW CPV plant in Alamosa, CO has 504 Amonix 7700 systems equipped with PMMA lenses from three vendors. This provides a good platform for a side-by-side comparison of these vendors. The plant has been in operation since March 1st, 2012. Since then, a large amount of data has been collected from these systems as well as three meterological stations. In addition, Amonix implemented a system in Pomona, CA to compare SOG lenses and PMMA lenses side-by-side. Seven months of data has been collected on this system. In this paper, we present the comparison of the PMMA lenses from three vendors as well as SOG lenses from one vendor in real world conditions.

9175-25, Session 7

Electroluminescence imaging of Morgan Solar's 4th generation CPV technology for in-line quality control and optical efficiency estimation

Michael Sinclair, Pascal Dufour, Kristine M. C. Drew, Morgan Solar, Inc. (Canada); Stefan Myrskog, Morgan Solar Inc (Canada); John Paul Morgan, Morgan Solar, Inc. (Canada)

Electroluminescence imaging is widely used in photovoltaic (PV) module manufacturing to identify defects in silicon PV cells. When a PV cell is illuminated under forward bias comparatively dark areas indicate defects such as cracks, poor soldering connections, discontinuities in the metallization, etc. An analogous test on a Concentrated PV system can be used to capture high resolution pseudo-efficiency maps that highlight optical defects in the concentrator system. Electroluminescence from a triple-junction cell under forward bias in a concentration optic results in a collimated beam of light. By imaging the output beam, one can estimate local and overall optical efficiency by analysing the intensity distribution of the emitted light. The experimental setup as well as key parameters of the imaging system are presented. Image processing is discussed, including comparison of experimental to nominal results and the quantitative estimation of optical efficiency. Efficiency estimates are validated using measurements under a collimated solar simulator and ray-tracing software. Further validation is performed by comparison of the electroluminescence technique to direct mapping of the optical efficiency. Initial prototype benchtop results indicate an estimation accuracy of better than 5% (3?) at the module level can be achieved, with a combined measurement and analysis time of less than 5 seconds per optic. An extension of this approach to in-line quality control is discussed.

9175-26, Session 7

On-sun performance of a commercial dish-based HCPV system

Blake M. Coughenour, The Univ. of Arizona (United States); Thomas E. Stalcup Jr., REhnu, Inc. (United States); Brian M. Wheelwright, Andrew Geary, Kimberly N. Hammer, The Univ. of Arizona (United States); J. Roger P. Angel, REhnu, Inc. (United States) and The Univ. of Arizona (United States)

REhnu Inc., with the University of Arizona, has developed a commercial dish-based High Concentration Photovoltaic (HCPV) system. The basic unit uses a paraboloidal glass reflector 1.65 m x 1.65 m square to bring sunlight to a high power point focus. A unique XRX-Köhler optical system

reformats the concentrated sunlight so as to uniformly illuminate 36 triple junction cells at 920x geometric concentration. The secondary optics and MJ cells are integrated with active cooling into a central, self-contained Power Conversion Unit (PCU) suspended above the dish reflector, which generates 800W of power for 1000W/m2 DNI at 32% DC net system efficiency.

Our 2nd generation prototype utilized a larger, 3.1 m x 3.1 m square mirror and consistently generated 2.7 kW of power normalized to 1kW/m2 DNI and has logged over 500 hours of on-sun testing. The 2nd generation unit operates at 28% DC net system efficiency with an operating cell temperature of only 20°C above ambient.

Having proven this system concept and cell cooling technology with low parasitic loss, our 3rd generation prototype was redesigned with a focus on manufacturability, lower cost, higher efficiency, and smaller size. This new 8lb handheld unit utilizes injection-molded plastic parts and minimal fasteners. Electrical connections and cooling connections are made to the PCU and the closed loop active cooling system is placed behind the mirrors on the two-axis tracking structure. Eight of these reflector/PCU units can be mounted on a single tracking structure.

9175-27, Session PWed

Analysis of a hybrid solar combined cycle in Algeria

Mohammed Laissaoui, Ctr. de Développement des Energies Renouvelables (Algeria)

The present work has for objective the simulation of a hybrid solar combined cycle power plant, compared with combined cycle conventional (gas turbine and steam turbine), this type of power plants disposed an solar tour (heliostat field and volumetric receiver) insurant a part of the thermal energy necessary for the functioning of the gas turbine

This solar energy serves to feed with heat the combustion air of the gas turbine when heout of the compressor and the front entered the combustion chamber.

The simulation of even central and made for three zones deferential to know the zone of Hassi R' mel, Bechare, and the zone of Messaad wilaya of El djelfa. The radiometric and meteorological data arise directly from the software meteonorme 7. The simulation of the energy performances is made by the software TRNSYS 16.1 chamber.

9175-28, Session PWed

Luminescent optical epoxies for solar concentrators

Anni Partanen, Aapo Harju, Jarkko Mutanen, Hanna Lajunen, Tuula Pakkanen, Markku Kuittinen, Univ. of Eastern Finland (Finland)

Luminescent solar concentrators were discovered in 1970s to lower the cost of solar cells by reducing the area of solar cell. These concentrators consisted of polymer containing luminescent dye. Afterwards quantum dots have also been used in a similar way in solar concentrators. The matrix material used in solar concentrator should have high transmittance in the visible region, and the dye should have low self-absorbance and high quantum efficiency.

We have fabricated luminescent optical epoxies and studied their luminescence properties. Fluorescein, Rhodamine B, 2,5-diphenyloxazole, trans-stilbene and Erythrosin B were separately mixed with Bisphenole A epoxy resin (Bisphenol A diglycidyl ether) which was cured with with Isophorone diamine hardener. Two different micropatterns were transferred to the epoxy samples during the hardening using cyclo-olefin polymer mold with an efficient and straightforward method.

The micropatterns were copied adequately in the epoxy surface, which would also suggest that nanopatterning would also be possible. Furthermore, the ability to pattern the surface allows fabrication of for example anti-reflective, hydrophobic and self-cleaning structures. Transmission measurement's show high transmittance (approx. 90%) of the epoxy matrix in visible region (350–800 nm), which is requirement for a good luminescent solar concentrator. Autoluminescence of the epoxy enables the use of UV radiation from sun. In addition the epoxy matrix should also protect the luminescent material from, e.g., oxidation and wear.

9175-29, Session PWed

High temperature concentrator solar cells for hybrid energy convertors

Jonathan Grandidier, Bill J. Nesmith, Subbarao Surampudi, Jet Propulsion Lab. (United States)

We are considering a high efficiency concentrator solar cell operating at high temperature. The advantage of high temperature photovoltaics (PV) is the possibility to integrate it with thermal energy convertor. High temperature PV could also be used in extreme environment such as planet from the inner solar system. Understanding optical and electrical performance of solar cells as a function of time and under various operating conditions including temperatures and thermal fluxes is critical to being able to predict the long term lifetime, reliability, life cycle cost and performance of concentrator PV systems. Our baseline photovoltaic energy conversion device is a high efficiency triple junction solar cell made of Indium Gallium Arsenide (InGaAs) for the top junction, Gallium Arsenide (GaAs) for the middle junction and (Ge) for the bottom junction. Ge is also used as a wafer for solar cell growing. In our proposed system, the solar spectrum is concentrated onto the solar cell and a fraction of the light depending on the PV temperature is converted into electricity. Measurements for these types of cells to at least 250C show that the conversion efficiency drops linearly by .04%/ C. The particularity of the proposed system is that all the heat resulting from non-converted light is used as the input for a thermal energy conversion engine. For a reasonably efficient engine the total electrical output optimizes at a value greater than the PV alone somewhere in the 250C to 400C range.

9176-1, Session 1

Surface science investigations of hematite-based photoelectrocatalysts *(Keynote Presentation)*

Bruce E. Koel, Peng Zhao, Coleman X. Kronawitter, Princeton Univ. (United States)

We report on fundamental studies of surface structure and reaction chemistry associated with the heterogeneous oxidation of water on hematite (?-Fe2O3)-based photoanodes that are promising materials for photoelectrochemical hydrogen generation. Applying a classical surface science approach, we have utilized a range of techniques for surface analysis to characterize the structure and properties of Ni-doped and mixed-oxide hematite surfaces formed by vapor deposition under controlled conditions. The structure of Ni-modified thin films of ?-Fe2O3 model catalysts with different morphology and geometry was characterized by LEED and STM. Then, water adsorption and reaction were studied by TPD, XPS, UPS, and vibrational spectroscopy by HREELS, characterizing the influence of Ni-modification on thermal and photochemical reaction mechanisms. Ni doping is found to be associated with a new termination for the ?-Fe2O3(0001) film. Water TPD shows that Ni doping induces new surface chemistry, as revealed by a new, higher temperature OH recombination desorption peak, which is due to more stable surface-bound OH groups as identified by UPS. These surface-science type experiments were combined with photoelectrochemical water oxidation measurements on photoanodes prepared by thin-film and nano-materials synthesis to elucidate new information on the surface phases of hematite-based photoanodes and about their specific stability and reactivity toward photoelectrochemical water splitting.

9176-2, Session 1

The role of fast charge dynamics in the water oxidation reaction *(Invited Paper)*

Tanja Cuk, Univ. of California, Berkeley (United States)

The early steps of water oxidation are investigated during catalysis with transient optical spectroscopy. Experiments on n-SrTiO3 with high quantum efficiency for O2 evolution under laser excitation (~80%) record how the interfacial kinetics change dramatically with the potential at which holes sit at the interface. The potential of holes at the interface is tuned continuously in a unique manner: by a carrier inversion process that unpins the valence band edge under applied voltage and light excitation. This continuous tuning enables us to determine spectroscopically the activation barrier for interfacial charge transfer during the early steps of water oxidation. For n-SrTiO3, this barrier is determined in a regime of high over-potential. In parallel, experiments on a photodiode activated Co3O4 catalyst aim to understand this charge transfer barrier in a regime of low over-potential.

9176-3, Session 1

Interfacial electronic structure and confinement effects for low-cost solar water splitting *(Keynote Presentation)*

Lionel Vayssieres, Xi'an Jiaotong Univ. (China)

The development of low cost metal oxide semiconductor heteronanostructures consisting of highly pure quantum dots/rods entirely fabricated from metal salts and aqueous chemistry without surfactant and at low temperature with controlled surface chemistry and intermediate bands for efficient visible-light conversion and highly quantized band structure for band/bandgap engineering is demonstrated. Such unique characteristics, combined with in-depth investigation of their electronic structure at synchrotron radiation facilities, optical, structural and transport properties provide comprehensive fundamental understanding of the energetics and structure-property relationships as well as key trends for efficiency optimization. Quantum dot-sensitized oriented iron oxide quantum rods showing full visible light absorption and stability against photo-corrosion for efficient and low cost hydrogen generation by direct solar (sea)water splitting at neutral pH is presented. Finally, the latest advances in size effects on electronic structure, surface chemistry and electrical properties of large bandgap oxide semiconductor will be presented and discussed for solar hydrogen generation improvement.

9176-4, Session 1

The chemistry of adsorbed water on semiconductor surfaces for aqueous photoelectrochemistry *(Invited Paper)*

Coleman X. Kronawitter, Bruce E. Koel, Princeton Univ. (United States)

The surface chemistry of water molecules adsorbed on single crystals, model structures relevant to photoelectrode-water interfaces in solar photoelectrochemical systems, is discussed. In heterogeneous processes relevant to photoelectrochemistry, the interaction of water with semiconductor and metal oxide surfaces is often a critical event whose character influences subsequent chemical pathways that ultimately dictate the reactions' efficiencies and selectivities. For reactions where water is neither reactant nor product, the presence of water at the interface can nonetheless influence both the selectivity and efficiency of interfacial charge transfer. An experimental surface science approach is used to characterize adsorbed water molecules on copper oxide and other semiconductor surfaces known to actively facilitate solar energy conversion in photoelectrochemical fuel synthesis devices. In this approach, ultra-high vacuum conditions are used to facilitate the fabrication of highly characterizable adsorbate systems, and the use of single crystal substrates permits analysis of surface chemistry independent of sample grain boundaries and morphology. An understanding of the surface chemistry of adsorbed water is developed through core-level spectroscopies, scanning probe microscopy, as well as analysis of desorption products from thermal reactions.

9176-5, Session 1

Development of a low cost, portable solar hydrogen generation device

Kyle D. Rose, Manmohan D. Aggarwal, Ashok K. Batra, Alabama A&M Univ. (United States); Dennis Wingo, Skycorp Inc. (United States)

Hydrogen is a clean energy source that is environmentally friendly and safe. It is well known that electrolysis is a common method used to produce hydrogen. Other high cost methods for hydrogen production can be countered by the development of this low cost pulse width modulated circuit, using direct current provided by naturally existing solar energy as a power source. Efforts are being made in the scientific community to produce a low cost, portable, solar hydrogen generating device for a number of clean energy applications such as fuel cells and energy storage. Proof of concept has already been tested in the laboratory and a small prototype system is being designed and fabricated in the workshop at Alabama A&M University. Our results of this study and details of the electronic circuit and the prototype shall be presented.

9176-6, Session 2

Visible light active materials for efficient photoelectrochemical hydrogen production *(Keynote Presentation)*

Sanjay Mathur, Univ. zu Köln (Germany); Leonhard Mayrhofer, Fraunhofer-Institut für Werkstoffmechanik (Germany); Markus Niederberger, ETH Zürich (Switzerland); Jan Augustynski, Univ. of Warsaw (Poland); Joan Ramon Moranted, Institut de Recerca en Energia de Catalunya (Spain); Helge J. Lemmetyinen, Tampere Univ. of Technology (Finland); Davide Barreca, Univ. degli Studi di Padova (Italy); Volkmar Lüthen, Siemens AG (Germany); Bernd Proft, Sachtleben Pigment GmbH (Germany)

The photoelectrochemical (PEC) water splitting is an alternative to transform abundant solar energy directly to eco friendly hydrogen as a storable fuel without carbon footprint. The aim of this single step transformation is to produce hydrogen directly from sea water only by using sun light and a suitable semiconductor as photoactive material. In order to drive these reactions, such semiconductor materials should provide a sufficient band gap (1.8-2.2 eV) with band edges well aligned to the redox potentials of water enable them to efficiently harvest sun light and provide charge carries for the electrochemical water splitting surface reactions. Furthermore those materials should be stable in aqueous environment, non toxic, abunded and cheap for industrial production. Transition metal oxides like TiO2, WO3 or Fe2O3 are interesting candidates for such applications. Even so this systems has been intensely investigated they still suffer from some drawbacks, like an inefficient light harvesting or fast recombination of generated charge carries, hindering there industrial applications. In order to overcome those drawbacks material modifications are needed.

We here present our recent results from the SOLAROGENIX project (EC-FP7 Grant No. 310333) starting from theoretical modeling to the synthesis and device integration of new photoelectrochemical material systems. We demonstrate the development of novel multi-functional nano crystalline photo active materials by different synthesis and post synthetic material modification strategies, which can be either wet chemical or gas phase approaches.

9176-7, Session 2

Homogeneous and heterogenized iridium water oxidation catalysts *(Invited Paper)*

Alceo Macchioni, Univ. degli Studi di Perugia (Italy)

Water oxidation is supposed to be the critical step of an artificial photosynthetic process aimed at producing solar fuels [1]. Although several materials and molecular species capable of catalyzing water oxidation have been reported, the performances are far to be of practical interest. Among molecular catalysts, iridium pre-catalysts have been attracting much attention over the last few years [2] because they exhibit remarkable TOF and TON values. We contributed to this field by synthesizing the iridium catalysts with the highest TOF reported so far [3] and developing robust iridium catalysts with dandling functionalities suitable to be anchored on photoactive materials [4]. At the same time, we started a systematic investigation on the transformation of the catalysts when subjected to “oxidative stress” [5] and on the reaction mechanism [6]. Our recent results are illustrated in this contribution.

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9176-8, Session 2

N-doped ZnO nanorod arrays with gradient band structure for photoelectrochemical water splitting *(Invited Paper)*

Shaohua Shen, Liang Zhao, Xi’an Jiaotong Univ. (China)

Solution based ZnO nanorod arrays were modified with controlled N doping by an advanced ion implantation method, and then utilized as photoanodes for PEC water splitting under visible light irradiation. An obvious N dopant concentration of 3.5 wt% was acquired by varying the implantation doses up to 1?1015 ions/cm2. N doped ZnO nanorod photoanodes displayed markedly enhanced PEC performance, a photocurrent of 150 ?A/cm2 was achieved under visible light illumination, which was about 2 orders of magnitude higher than that of pure ZnO. A comprehensive characterization was performed to explore how N dopant influences the physicochemical properties of ZnO nanorod arrays acting as water-splitting photoanodes. The relationship between optical properties, band structure, photoluminescence intensity and PEC performance indicated that gradient N ion doping can extend optical absorption ability, introduce internal driving force for photo-induced charge transfer and hence increase the PEC performance of ZnO nanorod arrays. These results proposed the potential application of ion implantation method for exploiting novel water splitting materials with improved visible light response.

9176-9, Session 2

Investigation of solar hydrogen generation from the GaN and InGaN thin films

Peifen Zhu, Takahiro Toma, Chee-Keong Tan, Nelson Tansu, Lehigh Univ. (United States)

Generation of hydrogen with low cost method is important for providing the clean energy in various energy consuming applications. One of the methods is to use TiO2 material in photoelectrochemical cell (PEC), however, the solar-to-hydrogen conversion efficiency is low due to the low solar energy absorption. Finding the suitable catalyst materials with the nonhazardous feature is necessary to provide high efficiency in the clean hydrogen generation. GaN-based material has been demonstrated for successful clean hydrogen generation, proving to be a suitable material for PEC application. Therefore it is important to systematically study the different material system for further enhancement solar-to-hydrogen conversion efficiency.

In this work, we systematically investigated GaN-based material in PEC with the comparison of various types of GaN-based thin films. The types of GaN-based thin films are categorized into n-GaN, u-GaN, p-GaN, and p-InGaN thin films. Hydrogen evolution was observed for n-GaN, u-GaN and p-GaN, p-InGaN thin films as working electrode under one sun AM 1.5 illumination. Current density of 1.73 mA/cm2 and 0.80mA/cm2 were achieved for n-GaN and u-GaN, respectively, at applied voltage of 1.2 V. The solar-to-hydrogen conversion efficiency of different thin films are described through measured current density as a function of applied voltage. The n-type thin film is shown to have higher efficiency of 0.7% in converting solar energy into hydrogen as compared to un-doped (0.3%) and p-type thin film, due to the lower resistivity in the n-type material, which is 0.008 Ohm?cm compared to the u-GaN (0.161 Ohm?cm) and p-GaN (4.73 Ohm?cm). Further details of the mechanisms behind the chemical reactions in these thin films will be discussed through various experimental measurements, and comparison of the results with ternary samples will be discussed.

9176-10, Session 3

Charge transfer dynamics at semiconductor quantum dot interface for solar energy conversion *(Keynote Presentation)*

Yasuhiro Tachibana, RMIT Univ. (Australia)

Semiconductor quantum dot (QD) is one of the most attractive nanomaterials for solar energy conversion devices. With their relatively large extinction coefficients and a wide light absorption range over visible wavelengths, QDs can be effective light absorbers. QDs are generally synthesized and handled in solution phase, facilitating solution processed device assembly. However, despite these attractive properties, controlling exciton states and charge separation and recombination dynamics has been challenging. For example, the excited electron and hole can readily be trapped by the surface states, losing initial excited energy. Charge separation of QD-TiO2 interface is relatively slow compared to dye sensitized system, which may compete with charge trapping process or exciton state decays. In this presentation, we will show quantitative analysis of charge trapping in QDs and demonstrate relationship of the QD nanostructures with the interfacial electron transfer reactions.

Several types of QDs with a narrow size distribution are synthesized to control the potential energy levels of the conduction and valence bands. We then analysed influence of QD surface states on the interfacial charge transfer dynamics. The interfacial structure is modified to control the dynamics. The relationship between the QD surface/interfacial structure and solar cell performance will be discussed.

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9176-11, Session 3

A novel Co-Pi capped pyramidal BiVO4 nanorod arrays with enhanced solar water oxidation *(Invited Paper)*

Jinzhan Su, Yankuan Wei, Liejin Guo, Xi'an Jiaotong Univ. (China) and International Research Ctr. for Renewable Energy (China)

Photoelectrochemical (PEC) water splitting is a promising strategy for the capture and storage of the abundant solar energy. In which, development of effective OER catalysts is a major challenge in energy conversion and storage. A simple but effective cobalt–phosphate water oxidation catalyst (Co-Pi) was reported by Nocera. Co-Pi has previously been deposited on the flatten BiVO4 thin film and showed a superior performance for water oxidation. In the present work, we report a Co-Pi capped BiVO4 nanowire arrays with Co-Pi selectively photodeposited on the tips of BiVO4 nanowires. The pyramidal-shaped BiVO4 nanowire arrays are synthesized in aqueous solution by the seed-layer mediated growth on FTO and then Co-Pi was photochemical deposited on the tips of BiVO4 nanowires. The comparison of the photocurrent-voltage characteristics of the BiVO4 electrodes with and without the presence of Co-based catalyst demonstrated that the catalyst generally enhanced the anodic photocurrent of the BiVO4 electrode and this enhancement showed more pronounced at lower potential. The mechanism of selectively photodeposition of Co-Pi on the tips of BiVO4 nanowires was discussed and was attributed to hole aggregation on the pyramidal shape of BiVO4 nanowires. This study may provide important new understanding of the enhancement and limitations of the Co-Pi catalyst coupled with semiconductor electrodes for water-splitting applications.

9176-13, Session 4

Solution synthesis of advanced materials for solar hydrogen *(Keynote Presentation)*

Gunnar Westin, Uppsala Univ. (Sweden)

The development of catalysts for solar fuels, solar cells and photo-assisted water and air cleaning require robust, routes capable of producing advanced complex materials. These multi-functional devices should both be effective in absorbing photons to generation of holes and electrons, charge transport and catalysis of surface reactions. Quantum confinement in typically less than 3-4 nm sized oxide systems may also be utilized for improved charge separation and transport properties which puts high demands on the precision of the processing routes. For such tough demands solution based routes are the best suited, but there is a need for further development of well understood, flexible routes to high quality, complex nano-structures. Here solution based processing routes to doped and non-doped oxide nano-particles, thin- and ultra thin films are presented. The oxide systems involve doped and non-doped Fe2O3, TiO2, ZnO, spinel and perovskite nano-particles, films and ultra-thin films, as well as metal nano-particles and ultra-thin films. The synthesis and prodcts were studied by a wide array of techniques including; SEM, TEM, XRD, TGA, DSC/DTA, IR-, Raman and UV-Vis-NIR spectroscopy.

9176-14, Session 4

The effect of temperature in flux-assisted synthesis of SnNb2O6

Dalal A. Noureldine, Kazuhiro Takanabe, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Water splitting using photocatalysis is a promising approach to provide the world's increasing energy demands from renewable and sustainable sources. A flux-assisted method was used to synthesize SnNb2O6 as a visible-light-responsive metal oxide photocatalyst. The role of flux was investigated in detail using different flux to reactant molar ratios (1:1, 3:1, 6:1, 10:1, 14:1) and different reaction temperatures (300, 500, 600 °C). The obtained products were characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM), Diffuse Reflectance UV-Vis Spectroscopy, X-ray photoelectron spectroscopy (XPS), the Brunauer-Emmett-Teller method (BET), and High Resolution Scanning Transmission Electron microscopy (HR-STEM). We successfully tuned the particle morphology by increasing the flux to reactant molar ratio, which afforded defined particles with non-aggregated surfaces. The XRD patterns and SEM analyses confirmed a 2D anisotropic growth along the bc plane, providing a plate-like morphology as the flux ratio increased. The DR.UV-Vis spectra of the obtained samples were consistent with the formation of SnNb2O6 in a single phase. The photocatalytic activity for hydrogen evolution was enhanced as the flux ratio was increased, reaching the highest value at a 1:10-F ratio. This result was explained by the beneficial role of increased flux in allowing the formation of tin niobate at a lower reaction temperature than with solid-state synthesis. This heightened activity coincides with the minimized amount of Sn4+ on the surface boundaries, which may act as trap states. The HR-STEM observation revealed that no preferential deposition of Ag, Pt and PbOx nanoparticles was observed depending on the surface facets of SnNb2O6.

9176-15, Session 5

High efficiency and highly stable water splitting on InGaN nanowire arrays under visible light irradiation *(Keynote Presentation)*

Zetian Mi, Md. G. Kibria, Bandar M. Alotaibi, McGill Univ. (Canada)

Recently, metal-nitrides (GaN and InGaN) have emerged as a viable photocatalyst for solar water splitting under ultraviolet, visible and potentially infrared light irradiation. By engineering the surface charge properties of InGaN nanowire arrays using Mg-dopant, we have demonstrated the absorbed photon conversion efficiency for InGaN nanowire photocatalyst can reach above 50%. Moreover, we have developed multi-band InGaN nanowire photocatalysts and photoelectrodes that can exhibit efficient and stable water splitting and hydrogen generation under ultraviolet, blue, and green light irradiation.

The realization of spontaneous water splitting under red and infrared light irradiation is being investigated and will be reported.

9176-16, Session 5

Electronic structure and interfacial phenomena in the generation of solar fuel characterized by In situ x-ray spectroscopy *(Invited Paper)*

Chung-Li Dong, National Synchrotron Radiation Research Ctr. (Taiwan); Jinghua Guo, Lawrence Berkeley National Lab. (United States)

In relation to the energy crisis and the global extreme climate, much attention is currently being paid to renewable energy resources. The search for new sources of clean energy is rapidly becoming one of the most pressing technological challenges that we are facing today. Enormous progress has been made in developing new materials that are tailored by nanostructuring, and other advanced synthesis methods. In many important energy systems such as solar energy conversion, electronic structure and fundamental interfacial phenomena play crucial roles in material performance. Without knowledge of the fundamental electronic and atomic structures of the materials and the changes of those structures upon reaction, better engineering the material for more practical purposes is impossible. To understand and ultimately control the interfaces in solar fuel generation calls for in-situ/operando characterization tools in which x-ray spectroscopy offers many unique features. X-ray absorption probes the local unoccupied electronic structure and x-ray emission probes the occupied electronic structure. The addition of resonant inelastic soft-x-ray scattering can tell the energy levels that reflect the chemical and physical properties. This presentation reports the development of in-situ reaction cells for x-ray spectroscopy towards the recent studies of photosynthesis, electrochemical and catalytic reactions. The challenge to monitor the electronic structure under operando condition has been that x-rays cannot easily peek into a high-pressure catalytic cell or a liquid photoelectrochemical cell. The successful development of the in-situ cell has overcome the barrier. A number of experimental studies are presented and suggest that in-situ/operando x-ray spectroscopy becomes a useful tool for investigating renewable energy materials in working conditions.

9176-17, Session 5

Hierarchical TiO2/In2S3 nano-heterostructures for high efficiency photoelectrochemical hydrogen generation

Mehrdad Balandeh, Alessandro Mezzetti, Fabio Di Fonzo, Istituto Italiano di Tecnologia (Italy)

In this study we report synthesis and characterization of quasi-1D hyperbranched TiO2 nanostructures sensitized with In2S3 quantum dots (QDs) in order to broad the light absorption spectra to the visible region as a photoanode for hydrogen production. The hierarchical nanorostructures have better electron mobility and charge transport than nanoparticles also has very large surface area even larger than branched nanorods (B-NRs). TiO2 has low efficiency for photoelectrochemical hydrogen production due to its large bandgap but it can provide the large surface area, high charge mobility, light harvesting/scattering. In the other hand the In2S3 has lower bandgap and can absorb light in the visible region. The TiO2 hierarchical nanostructure film was deposited by Pulsed Laser Deposition (PLD) technique. The PLD technique is well known as a technique that can grow wide range of metal oxides with a complex morphology and high surface area. The as deposited films were amorphous so the 2 hours annealing at 500 ˚C in air was performed to obtain the anatase crystalline phase. The hierarchical nanostructure TiO2 synthesis by PLD was sensitized by In2S3 quantum dots. The sensitization was performed by successive ionic layer absorption and reaction (SILAR) technique which is able to deposit a very uniform and thin layer all over this complex structure. The In2S3/TiO2 photoelectrochemical performance was characterized by using an electrochemical workstation coupled with a solar simulator.resulting in 1 mA.cm-2 current density under solar simulator illumination (solar spectrum matched to AM 1.5G, 100 mW/cm2 total power density).

9176-18, Session 6

Functionalization of Ag nanoparticles using local hydrophilic pool segment designed on their particle surface *(Invited Paper)*

Motoyuki Iijima, Yokohama National Univ. (Japan); Aki Kurumiya, Junki Esashi, Hayato Miyazaki, Hidehiro Kamiya, Tokyo Univ. of Agriculture and Technology (Japan)

Recently, an improvement in the light conversion efficiency of dye-sensitized solar cell (DSSC) by introducing Ag nanoparticles which possesses localized surface plasmon resonance effects into the electrodes has attracted wide attention. In order to effectively improve the properties of DSSC with Ag nanoparticles, appropriately designing their particle surface to control their dispersion stability during fabrication of electrodes and to maintain chemical stability of Ag nanoparticles are key issues. In this report, a new processing route to fabricate Ag nanoparticles those coated with thin SiO2 layer and dispersible in various organic solvents have been designed. First, Ag nanoparticles those have local hydrophilic pool structure and dispersible in various organic solvents have been fabricated through a layer-by-layer surface modification process on the Ag nanoparticles using cationic polyethyleneimine and anionic surfactant. An anionic surfactant that having an organic chain comprised from hydrophilic PEG chain and hydrophobic alkyl chain near the head group was chosen since it was reported to improve the stability of nanoparticles in various organic solvents. The surface modified Ag nanoparticles were then dispersed into toluene and treated with tetraethyl orthosilicate (TEOS). It is expected that the hydrolysis and condensation reaction of TEOS occurred in the local hydrophilic pool segment designed on Ag nanoparticles and successfully resulted to obtain Ag nanoparticles coated with thin SiO2 shell those were dispersible in various organic solvents.

9176-19, Session 6

Plasmonic Ag nanoparticles-decorated p-type Si wire array as photocathode for water splitting

Chih-Jung Chen, National Taiwan Univ. (Taiwan)

We utilized Ag nanoparticles decorated-Si wire array (Ag/Si) as the photocathode for water splitting. The p-type Si wafer was etched by inductively coupled plasma (ICP). The pitch size of Si wire array is ~2?m, and the diameter and length of single wire are ~1 ?m and 12 ?m respectively. The one dimensional structure of Si wire was promote the photoresponse by shortening diffusion length for minor carriers and providing major carriers for single conducting direction. We also decorated Ag nanoparticles on the Si wire array through simple redox reaction method. The overpotential of Ag/Si photocathode was decreased by the assistance from Ag co-catalyst. The onset potential of Ag/Si electrode shifted to ~0 V (vs RHE). In addition, the photocurrent of Ag/Si photocathode was further enhanced by surface plasma resonance (SPR) assistance. The two primary mechanisms of plasmonic enhanced-water splitting were hot electrons injection and plasmon-induced electromagnetic fields. The electrons near the Fermi level of Ag nanoparticles were excited to high energy state under solar illumination. These high energy electrons were so-called hot electrons. The hot electrons directly overcame Schottky barrier and injected into the conduction band of Si wire to increase the photocurrent. In the other way, the electron-hole pairs forming probability of Si wire was strongly affected by the surrounding electric fileds. The electric fields of SPR

inhomogeneously distribute on Ag nanoparticles. The charge-carriers easily generated near the interface of Si wire and Ag nanoparticles to reduce the recombination.

9176-20, Session 6

Nanoporous GaN for enhanced solar hydrogen production

Jonathan D. Benton, Jie Bai, Tao Wang, The Univ. of Sheffield (United Kingdom)

III-nitride semiconductor materials (InN, GaN, AlN) have the potential to span the majority of the solar spectrum due to their direct bandgaps spanning from 0.7 eV through to 6.2 eV. Moreover, III-V materials have demonstrated remarkable resistance to corrosion in various electrolyte solutions and have the required conduction and valence band positions making them ideal for photocatalytic hydrogen production. Porous materials for solar hydrogen have been widely reported to improve photocurrent. Here we report the fabrication of porous GaN/InGaN planar and nanostructured devices for solar hydrogen production that results in a significant increase in device performance.

Photoelectrochemical etching was employed to create the porous structure via the utilisation of a KOH solution as the etchant, a 300 W ozone-free xenon lamp as the light source and a platinum rod as the counter electrode. A controllable porous structure has been obtained on as-grown GaN/InGaN wafers and GaN/InGaN nanorods. Under photoelectrochemical testing with 1 sun illumination a lasting enhancement in photocurrent is obtained in both device architectures. A factor of up to 5 is observed in the as-grown devices as a result of the porous structure, which we attribute to the increased surface area and a scattering of incident radiation. The combination of a disordered pore structure within a nanorod array provides further gains in device performance of a factor of 2 attributed to the enhanced electron-hole separation observed in the nanorod structure.

9176-21, Session 6

Nanostructured Cu2O/SrTiO3 heterojunction for solar hydrogen production: experimental and first-principles analysis

Dipika Sharma, Anuradha Verma, Anamika Banerjee, Vibha R. Satsangi, Rohit Shrivastav, Dayalbagh Educational Institute (India); Umesh V. Waghmare, Jawaharlal Nehru Ctr. for Advanced Scientific Research (India); Sahab Dass Kaura, Dayalbagh Educational Institute (India)

Nanostructured thin films of pristine SrTiO3, Cu2O and Cu2O/SrTiO3 heterojunction with varying thickness of SrTiO3. SrTiO3 and Cu2O thin films were deposited on ITO glass substrate using sol–gel spin-coating technique and spray pyrolysis method respectively. Among various metal oxide semiconductors, cuprous oxide Cu2O and strontium titanate SrTiO3 were chosen for the present study on account of being abundant, non-toxic, and environmentally safe and possess staggered type band edges which are suitable for efficient charge separation. SrTiO3 is the wide band gap material (3.2 eV) while Cu2O is low band gap material (2.3eV), which is responsible for visible light absorption. All samples were characterized using X-ray diffractometer (XRD), Scanning electron microscopy (SEM) and UV–Vis spectrometry. The influence of surface modification of Cu2O with varying thickness of SrTiO3 on PEC performance has been investigated. Our results showed that the photocurrent density of the Cu2O/SrTiO3 heterojunction thin films with overall thickness of 343 nm was 2.52 mAcm-2 which is higher than that of pristine Cu2O 0.10 mAcm-2 at 0.8 V/SCE . The effective mass for electron and holes at the conduction band minima and the valence band maxima, were also calculated using DFT based calculations for Cu2O and SrTiO3. It was found that the electrons in SrTiO3 had large effective masses (i.e. weak mobility) as compared to electrons in Cu2O (i.e. strong mobility) at conduction band minima near ? point. The difference in the mobility of photogenerated electrons for bulk SrTiO3 and Cu2O may significantly contribute in photo-generated charge carrier separation at the Cu2O/SrTiO3 interface leading to the enhanced photocurrent density.

References: [1] Dipika Sharma, Anuradha Verma, V.R.Satsangi, Rohit shrivastav, Sahab Dass Nanostructured SrTiO3 thin films sensitized by Cu2O for Photoelectrochemical Hydrogen Generation International journal of Hydrogen Energy http://dx.doi.org/10.1016/j.ijhydene.2013.12.201

9176-22, Session 6

Plasma-enhanced CVD of visible-light active metal oxide nanostructures: growth, modification, and device applications

Andreas Mettenbörger, Thomas Fischer, Yakup Gönüllü, Ashish Lepcha, Sanjay Mathur, Univ. zu Köln (Germany)

Application of tailor-made molecular precursors in plasma-enhanced chemical vapor deposition (PE-CVD) techniques offers a viable solution for overcoming thermodynamic impediments involved in thin film growth. The use of cold plasmas enables the realization of various functional coatings whose application spectrum spans from transparent conductive coatings, scratch-proof films, photoactive to anti-bacterial materials. Over the past decade, we have developed several new precursor systems in order to demonstrate the competitive edge of molecule-based plasma coatings. Our work on a large number of metal oxide systems and their characterization towards microstructure, compositional and functional properties supports the advantages of chemical design in simplifying deposition processes and optimizing functional behaviour.

This talk will present how properties of hematite thin film can be changed by PE-CVD technique by changing the process parameter. In this work, thin films of hematite were prepared at different RF-power using iron pentacarbonyl as a precursor with oxygen as reactive gas. The resulting thin films were used as a photoelectrode in photoelectrochemical cell to study the solar water oxidation under illumination in 1M NaOH electrolytes. The ?-Fe2O3 photoanodes deposited at high RF-power, an enhancement in the photocurrent density was observed. These results demonstrate that the controlled growth of hematite film with tunable morphology provides an efficient photoanode for photoelectrochemical water splitting application which is obtained by the proper chosen of process parameters.

9176-23, Session 6

Facile synthesis of p-type Zn-doped ?-Fe2O3 films for solar water splitting

Chun-Lin Kuo, Yu-Kuei Hsu, National Dong Hwa Univ. (Taiwan); Yan-Gu Lin, national synchrotron radiation research center (Taiwan)

A facile and simple fabrication of Zn-doped alpha-Fe2O3 thin films as a photocathode for solar hydrogen generation was proposed in this report. Transparent Zn-doped alpha-Fe2O3 films were prepared by a deposition-annealing (DA) process where nontoxic iron(III) chloride represents the Fe precursor and zinc chloride represents an acceptor dopant, followed by annealing at 550 Celsius degree in air. In terms of the structural examination of as-grown samples, X-ray diffraction analysis demonstrated an increase in the lattice parameters of Zn incorporated in Fe2O3 by substituting Fe in the host lattice. No second phase was determined, indicating no phase separation in the ternary materials. Energy dispersive spectroscopy results demonstrated that Zn, Fe, and O elements existed in the deposits. Furthermore, impedance measurements show that the Zn-dopant serves as an hole acceptor and increases the acceptor concentration by increasing concentration of zinc precursor. Significantly, the photoelectrochemical measurements exhibited remarkable cathodic current, corresponding to the reduction reaction of hydrogen. Finally, the optimum photocurrent can be achieved by controlled variation of the Fe and Zni precursor concentration, annealing conditions, and the number of DA cycles. According to our investigation, the understandings of morphology effect on PEC activity give the blueprint for materials design in the application of solar hydrogen.

9176-24, Session 7

Materials for photoelectrochemical water splitting: The U.S. Department of Energy PEC working group *(Invited Paper)*

Heli Wang, National Renewable Energy Lab. (United States); Thomas F. Jaramillo, Stanford Univ. (United States); Eric L. Miller, U.S. Dept. of Energy (United States)

A durable photoelectrochemical (PEC) water splitting device with high solar-to-hydrogen (STH) conversion efficiency has been a significant materials challenge for decades. Critical requirements on semiconductor materials' band gap, band edges, optoelectronic efficiency, and stability must be satisfied simultaneously.

Metal oxide semiconductors may be stable and earth-abundant, STH efficiencies have been limited by issues related to the wide band gap, band-edge mismatch and the poor opotoelectronic quality in these materials. Tandem cell configurations have been developed to address the band-edges mismatch, more work is needed on overcoming the efficiency limitations due to absorption, charge mobility, recombination, interfacial kinetics, etc. On the other hand, crystalline III-V materials offer alternative pathway to efficient STH conversion, with suitable band gaps by justifying the range of compositions and optoelectronic quality. Moreover, the band edge mismatch has been successfully addressed using monolithic PEC/PV tandem cell design. Stability, however, remains a key issue. NREL, working with other members of the U.S DOE PEC Working Group have been investigating the corrosion of III-V materials and interfaces with a goal to develop surface modification methods for mitigating the corrosion issue. Approaches include coatings, ion bombardment, surface nitridation as well as electrolyte treatments.

Significant materials challenges remain, and effective usage of resources is needed. The PEC Working Group facilitates progress by bringing together diverse PEC researchers with common interests and goals, promoting collaborative activities, resource sharing, and joint publications.

9176-25, Session 7

Efficient and durable solar-driven hydrogen production with branched nanowire heterostructures

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Branched nanowire (NW) heterostructures have recently been attracted considerable attention for solar water splitting and clean hydrogen production due to their unique properties such as nanoscale integration of different functional materials, greatly enhanced junction and surface area, enhanced gas evolution efficiency, broadband light absorption, etc. Moreover, branched NWs can be fabricated using facile and scalable fabrication methods such as hydrothermal or solvothermal growth methods. In this presentation, we show branched NWs of different compositions for core (or trunk) and branch NWs which were fabricated with facile and low-cost synthesis methods using cheap, non-toxic, and earth abundant materials including Si, CuO, Cu_2O, ZnO, TiO_2, and Fe_2O_3. The branched NW structures and the heterostructures' interfaces are investigated in detail using different characterization techniques such as SEM/HRSEM, TEM/HRTEM, STEM/HRSETM, etc. The photoelectrochemical (PEC) performances including photocurrent turn-on potential, photocurrent, solar conversion efficiency, and incident photon-to-current efficiency (IPCE) are studied systematically and optimized, based on different core and branch NW dimensions, for each specific branched NW heterostructure to provide efficient water splitting in a neutral medium. The electrode stability of different branched NWs is also investigated and long-term stability of over one day or several hours using a thin passivation layer or robust branched NWs are presented. The achieved results pave the way for accomplishing spontaneous overall solar water splitting for clean, efficient, cost-effective and durable solar hydrogen generation at large scales.

9176-26, Session 7

Synthesis and photo-induced charge and energy transfer in novel luminescent CdSe QD: metal oxide composite heterostructures *(Invited Paper)*

Jinkyu Han, Brookhaven National Lab. (United States); Lei Wang, Stony Brook Univ. (United States); Stanislaus S. Wong, Brookhaven National Lab. (United States) and Stony Brook Univ. (United States)

Recently, the generation of QD- metal oxide nanoscale heterostructures has become the focus of particular interest, because the unique and distinctive physical and chemical properties of QDs and of metal oxides can potentially be tuned and tailored so as to render significant improvement and performance enhancement as compared with single component systems for various applications including but not limited to photo-catalysis, chemical sensing, microelectronics, and photovoltaics. In this report, we successfully synthesized novel luminescent zero-dimensional (0D) CdSe nanocrystal (with their size-dependent absorption properties) – multi-dimensional metal oxide (including various rare earth-doped analogues with their corresponding chemically and structurally defined PL attributes) nanoscale heterostructures. In addition, we have characterized interfacial electronic and optical interactions between single components (e.g., either charge or energy transfer) in these heterostructures using PL emission and time-resolved PL spectroscopies. Furthermore, we have investigated the effects of varying different morphologies of metal oxides upon the optical interactions in the heterostructures, incorporating CdSe QDs and different morphological motifs of metal oxides, including 0D, 1D, and 3D architectures. We suggest that these nanoscale heterostructures enable not only the ability to tune the optoelectronic properties of nanomaterials for possible incorporation into nanoscale devices but also the potential to design new types of photovoltaic architectures with the capability of effectively harvesting UV light as well as for promoting highly efficient charge separation.

9177-1, Session 1

IR-imaging and non-destructive loss analysis on thin film solar modules and cells

Jens Adams, Frank W. Fecher, Felix Hoga, Claudia Buerhop-Lutz, Bayerisches Zentrum für Angewandte Energieforschung e.V. (Germany); Christoph J. Brabec, ZAE-Bayern (Germany) and Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

CIGS thin film solar modules, despite their high efficiency, may contain three different kinds of macroscopic defects referred to as bulk defects, interface defects and interconnect defects. These occur due to the film's sensitivity to inhomogeneities during the manufacturing process and decreasing the electrical power output from a cell or module. In this study, we present infrared (IR) imaging and contactless loss analyses of defects contained in commercially manufactured thin film solar modules. We investigated different relations between the emitted IR-signal (using illuminated lock-in thermography ILIT) and the respective open circuit cell voltage (Voc) [1] as well as the maximum power point (Pmpp) [2]. A simulation study, using the 2D finite element method, provides a deeper understanding as to the impact on electrical performance when defects are present on the cell or module.

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[2] A. Vetter, et al., Lock-in thermography as a tool for quality control of photovoltaic modules, Energy Science & Engineering 1 (2013) 12–17

[3] F.W. Fecher, et al., Influence of a shunt on the electrical behavior in thin film photovoltaic modules - a 2D finite element simulation study, Solar Energy (submitted)

9177-2, Session 1

Test and Analysis of Thin Film Photovoltaic (TFPV) for UAV application

Mohammad Gadalla, Sayem Zafar, American Univ. of Sharjah (United Arab Emirates)

A study was conducted to investigate the performance of thin film flexible PV panels. The experimental study was conducted to simulate the performance of the panels for the conditions found during the unmanned aerial vehicle (UAV) flight in the city of Sharjah. Two 2 m and a single 1 m WaveSol Light PV panels were tested for the study. The 2 m panels are for each wing while the 1 m panel is for the horizontal stabilizer. WaveSol Light PV panels were considered for this research because of their relative light weight, high current and compatible voltage output. These PV panels also have a convenient width which can easily be mounted on the UAV wings and stabilizer. The panels were tested for power output at different angles and curvatures for varying solar flux. The curvature tests were performed to simulate the shape of the UAV's wing and horizontal tail airfoils. Different angles were also tested to study the power output during cruise and maneuvering. A detailed parametric study was also conducted to determine the power output with respect to the time of the day. The parametric study was important as it would help to predict the flight duration and the performance of the UAV for regular operations. The study predicted the optimal operating parameters for different angles and curvatures. It also established the time of the day yields the highest power output for its corresponding angle.

9177-3, Session 1

Synchronized thermography for multi-layer thin film characterization

Kimmo K. Leppänen, Juha M. Saarela, Tapio E. J. Fabritius, Univ. of Oulu (Finland)

Organic solar cells and organic LED´s are typically made of conductive and semi-conductive thin films. The uniformity requirement for these films is very high. In the case of multi-layer structures, surface characterization based methods (e.g. profilometer, atomic force microscope, scanning electron microscope) encounter remarkable challenges when attempting to detect uniformity differences because the defects can be inside the structure. To overcome this limitation, a synchronized heating and IR-imaging based system (called synchronized thermography = ST) was utilized for multi-layer structures. Indium Tin Oxide (ITO) was used as an example of conductive thin films and poly(3,4-ethylenedioxy-thiopene):poly(styrene-sulfonate) (PEDOT:PSS) was used as an example of a hole transporting layer. Uniformity differences were generated in these layers and ST was used to detect them. The results show that ST is capable of localizing small defects in a lateral direction in the stack using a single IR-image. Due to the remarkable conductivity differences of ITO and PEDOT:PSS, it can be estimated even in which layer the defect locates. This is a significant advantage in contrast to surface profiling measurements.

9177-4, Session 1

Photoluminescence of hydrogenated silicon with amorphous/nanocrystalline mixed phase

Andrey Emelyanov, Russian Research Ctr. Kurchatov Institute (Russian Federation); Pavel Forsh, Russian Research Ctr. Kurchatov Institute (Russian Federation) and Lomonosov Moscow State Univ. (Russian Federation); Mark Khenkin, Andrei G. Kazanskii, Lomonosov Moscow State Univ. (Russian Federation); Pavel Kashkarov, Russian Research Ctr. Kurchatov Institute (Russian Federation) and Lomonosov Moscow State Univ. (Russian Federation)

Hydrogenated amorphous silicon (a-Si:H) and nanocrystalline silicon (nc-Si:H), which consists of amorphous matrix with embedded silicon nanocrystals, are widely used in electronics and optoelectronics, in particular, in the production of photovoltaic cells and thin film transistors. nc-Si:H films with a small (10 - 15 %) volume fraction of Si nanocrystals are of particular interest. The focus of this work was the investigation of photoluminescence (PL) properties of nc-Si:H films with small volume fractions of the nanocrystalline inclusions.

The investigated nc-Si:H films were fabricated by means of PECVD technique. The volume ratio of gases in the reactor chamber RH=[H2]/[SiH4] was varied as follows: RH = 0 (reference a-Si:H film), 5, 8, 11 and 16. The structure of the films was studied from the analysis of the Raman scattering spectra measured by the micro-Raman spectrometer Horiba Jobin Ivon HR800. The PL spectra were recorded using a MS-3504i (SOLAR TII) spectrograph and a CCD camera (Hamamatsu) under excitation of 364 nm line of a continuous Ar-ion laser. During PL experiments samples were placed into vacuum cell of a DE-204N closed-cycle helium cryostat and cooled down to the temperature of 17 K.

Raman spectra analysis show that the volume fraction of crystalline phase in the films increases with the growth of RH from 0 (a-Si:H film) to 80 %. Using Raman spectra we have also estimated the average diameter of Si nanocrystals in the samples by the red shift of the maximum near 520.5 cm-1. The average diameter of Si nanocrystals is varied from 5 – 7 nm for the samples with RH > 5. A broad PL spectrum with the peak energy of about 1.35 eV is observed for a-Si:H at 17 K,

which is commonly attributed to recombination between electrons trapped in localized tail states of conduction band and holes trapped in localized tail states of valance band. The samples with RH > 5 also show an additional PL maximum near the photon energy of 1.52 eV. The crystalline phase volume fraction increase causes increasing of the PL maximum intensity. Observed maximum could be associated either with defect states on the boundary between Si nanocrystals and amorphous matrix or with the quantum confinement states in Si nanocrystals.

9177-5, Session 2

CIGS/organic single-junction and tandem hybrid solar cells

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Copper indium gallium diselenide (CIGS) solar cells are the most efficient thin film photovoltaic devices. In this work, we investigate CIGS/organic hybrid solar cells comprising semi-transparent metal top electrodes and wide-band gap organic semiconductors as buffer layer. Depositing the organic semiconductors from solution, we fabricate Cd-free CIGS solar cells exhibiting about the same efficiency as their fully inorganic counterparts comprising CdS, and significantly higher open-circuit voltages as compared to buffer-free devices. Although the organic molecules do not cover the CIGS surface homogeneously, their use enables prolonged charge carrier lifetimes according to impedance spectroscopy measurements.

Combining wide and narrow band gap absorbers in tandem solar cells is a promising approach to improve the energy conversion of sunlight. We therefore present hybrid tandem devices comprising monolithically connected CIGS bottom cells and polymer top cells. The thin polymer:fullerene bulk heterojunction absorber layers were transferred onto the rough CIGS surface by a soft-contact lamination technique. Sputtered or solution deposited top-cathodes complete the tandem devices with enhanced open circuit voltages.

Finally, we present CIGS solar cells incorporating solution-deposited transparent top cathodes. The utilized highly conductive polymer blend and the silver nanowire mesh exhibit excellent transparency in the near-UV region and form pinhole-free, homogeneous layers.

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9177-6, Session 2

Effects of sputtering technique on quaternary Sputtered Cu(In,Ga)Se2 Films

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While Cu(In,Ga)Se2 (CIGS) has established itself as the thin film photovoltaic material of choice with current record efficiencies in excess of 20%, current high-efficiency laboratory-scale fabrication techniques, such as multi-stage evaporation, are ill suited to mass production. Quaternary-sputtering is a promising alternative technique for CIGS deposition, where a single sputtering target made from CIGS itself in the desired stoichiometry is used as the sole deposition source. Devices made using this technique do not require any additional post deposition selenium treatment and have demonstrated peak efficiency in our laboratory in excess of 10%, showing the potential of quaternary sputtering. However, device efficiency to date has been limited by high surface roughness in films produced by conventional RF sputtering. X-ray diffraction and microscopy studies of grain nucleation and growth have attributed this to the long deposition times required using this deposition technique, allowing films to reorganize and grow preferentially in the (112) orientation. In an effort to reduce deposition times, we have fabricated films using pulsed DC sputtering, which substantially reduces the substrate time-at-temperature during absorber formation. DC-sputtered films are observed to have reduced surface roughness and different internal morphology than RF-sputtered films. Comparisons between RF- and DC-sputtered films will be presented, contrasting their crystallinity, grain structure, and device performance.

9177-8, Session 2

Fabrication of ultra-thin (~1 μm) CdTe layer by close spaced sublimation (CSS) techniques for CdTe/CdS solar cell application

Mohammad Rezaul Karim, King Saud Univ. (Saudi Arabia)

The limitation of the fossil resources to generate electrical energy is forcing the researcher to pursue research in the area of power generation through solar cells. Cadmium telluride (CdTe) has evolved in recent time as promising candidate for solar cell material. This thesis work has focused on fabrication of the thin film CdTe solar cell. Main focus was the depositions of CdS window layer and CdTe absorber layer. Prior to the real fabrication of the cell, photovoltaic characteristics of the cells with ultra-thin CdTe layer have been predicted by simulation through AMPS (Analysis of Micro Electronics and Photonic Devices Simulation) software. The absorber layer has been deposited by close spaced sublimation (CSS) method. This Close spaced sublimation system was custom built by our group. Very fine, pin hole free CdTe ultra-thin films were deposited by CSS. The work also constitutes the deposition of CdS layer as a window layer by chemical bath deposition and its characterization. The effect of annealing has also been studied.

The work also focused on the reduction of the CdTe absorber layer and its effect on the performance of the cells. Moreover, the CdZnTe is introduced at the top of the CdTe absorber layer in order to improve the performance of the cell which has ultra-thin CdTe layer of around 1-2 ?m. The insertion of a wider bandgap material, such as CdZnTe (bandgap 2.20eV) with a negligible valance band-offset to CdTe, introduced prior to the back contact that could inhibit the recombination of generated carriers by bouncing back to the CdS/CdTe junction. An improvement in the open circuit voltage and efficiency has been recorded.

9177-9, Session 2

Influence of the heat treatment temperature on the crystal structure of CuInS2 thin films prepared by non-vacuum technology

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In this study, CuInS2 semiconductor thin film for CIS thin film solar cell was prepared by sulfurizing CuIn precursor in non-vacuum system. The quality of CuInS2 semiconductor was improved by proper heattreatment. The crystalinity of CuInS2 was presented by Raman spectra. With the increase of the temperature of heattreatment, the In- rich defect phase showed decreasing. By 500oC heattreatment, the defect phase was almost disappeared. The open voltage of CuInS2 film changed from tens milivolts to 700 milivolts. The method would be useful in the manufacuture of CIS thin film solar cell in non-vacuum system.

9177-10, Session 3

Enhancement of perovskite-based solar cells employing core shell metal nanoparticles

Michael Saliba, Henry J. Snaith, Univ. of Oxford (United Kingdom)

In this study, we combined core–shell metal–dielectric nanoparticles within a thin-film solar cell technology employing a recently developed organometal lead halide absorber which shows great promise for high efficiency photovoltaic applications.

More specifically, plasmonic core-shell Au-SiO2 (80 nm @ 8 nm) nanoparticles were embedded into the mesoporous alumina structure of a perovskite solar cell.

At optimized conditions, devices with incorporated gold nanoparticles showed a significantly enhanced short-circuit photocurrent and average efficiencies of 9.5% as compared to control devices with 8.4% efficiency. However, we observed no significant enhancement in light absorption from the nanoparticles.

To investigate this effect further, we conducted a time-resolved and steady state temperature-dependent photoluminescence study resulting in the conclusion that the improved photocurrent was due to a reduced exciton binding energy, and thus enhanced generation of free charge carriers in the presence of metal nanoparticles.

This represents a new enhancement mechanism for metal nanoparticles incorporated into photovoltaics and may prove to be exceptionally useful for this new family of perovskite semiconductors where the exciton binding energy is in the order of 100 meV. We do note, however, that further work is required to fully understand the mechanism which is driving the enhanced solar cell.

[1] Zhang/Saliba et al., Enhancement of Perovskite-Based Solar Cells Employing Core–Shell Metal Nanoparticles, Nano Letters (2013)

9177-12, Session 3

Systematic study of metal-insulator-metal diodes with a native oxide

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In this paper, a systematic analysis of native oxides within a Metal-Insulator-Metal (MIM) diode is carried out, with the goal of incorporating them into a nanoscale Rectenna (Rectifying Antenna). MIM structures have electrical properties that could be better suited to this application than other diode structures, including higher achievable cut-off frequencies. Controlled deposition of stoichiometric ultra-thin oxides is required for optimal MIM diode performance. The requirement of having a sub-10nm oxide scale can be met by using the native oxide, which forms on most metals exposed to an oxygen containing environment. This, therefore, provides a simplified MIM fabrication process as the complex, controlled oxide deposition step is omitted. We shall present the results of an investigation into the current-voltage characteristics of various MIM combinations that incorporate a native oxide, in order to establish whether the native oxide is of sufficient quality for good diode operation. The thin native oxide layers are formed by room temperature oxidation of the first metal layer, deposited by reactive magnetron sputtering. This is done in-situ, within the deposition chamber before depositing the second metal electrode. Using these structures, we study the established trend where the bigger the difference in metal workfunctions, the better the rectification properties of MIM structures, and hence the selection of the second metal is key to controlling the device's rectifying properties. We show how leakage current paths through the non-optimised native oxide scale control the net current-voltage response of the MIM devices. Furthermore, we will present the so-called diode figures of merit (asymmetry, non-linearity and responsivety) for each of the best performing structures and discuss the suitability of such structures for use in a nanoscale rectenna.

9177-13, Session 3

New donor-acceptor type fluorinated quinoxaline-based polymer solar cells with prominent air stability and efficiency

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In this study, a new medium bandgap conjugated copolymer comprising of a rigidly fused BDT unit and a fluorinated quinoxaline moiety through a thiophene π?spacer has been rationally designed and synthesized by Stille coupling polymerization and thoroughly evaluated for use as a donor material in bulk-heterojunction polymer solar cells (BHJ PSCs). A comprehensive study of the structure-function relationship in the PSCs was also explored. Possessing an intrachain donor-accepter architecture, this polymer exhibits strong and broad absorption band across UV and visible region. Introducing highly electronegative fluorine atoms to quinoxaline moiety lowers both the highest occupied molecular orbital and the lowest unoccupied molecular orbital level of polymer, beneficial for attaining higher open-circuit voltage. Conventional architecture BHJ PSCs using PBDTQEH:PC71BM (1:1, w/w) displays a high power conversion efficiency of 5.90%. Compared with the same composition, device in the inverted configuration reveals a rather high PCE of 6.36% with a Voc of 0.78 V, a short-circuit current density of 12.72 mA cm-2, and a high fill factor of 64.3%. The inverted device also demonstrates outstanding air stability; the solar efficiency of the device remains above 74% of the original value after storage in air for 1000 h without any capsulation.

9177-14, Session 3

Microcrystalline silicon oxides for silicon-based solar cells: impact of the O/Si ratio on the electronic structure

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Most Si-based solar cell structures contain emitter/contact/passivation layers, which consist of the same/similar material as the absorber. Ideally, these layers fulfill their desired task (i.e., induce a sufficiently high internal electric field, ensure a good electric contact, and passivate the interfaces of the absorber) without absorbing light. Usually this leads to a trade-off in which a higher transparency can only be realized at the expense of the layer's ability to properly fulfill its task. One alternative approach is to use hydrogenated microcrystalline silicon oxide (?c-SiOx:H), a mixture of microcrystalline silicon and amorphous silicon (sub)oxide. The crystalline Si regions allow charge transport, while the oxide matrix maintains a high transparency. To date, it is still unclear how in detail the oxygen content influences the electronic structure of the ?c-SiOx:H mixed phase material.

We have used a combination of complementary x-ray and electron spectroscopies to study the chemical and electronic structure of the ?c-SiOx:H (0 < x = O/Si < 1) system. Different information depths of the employed techniques help to reduce the impact of surface oxides on the spectral interpretation. For all samples, we find the valence band maximum to be located at a similar energy with respect to the Fermi

energy. However, for x > 0.5, we observe a pronounced decrease of Si 3s – Si 3p hybridization in favor of Si 3p – O 2p hybridization in the upper valence band. This coincides with a significant increase of the material's resistivity, possibly indicating the breakdown of the conducting crystalline Si network.

9177-15, Session 4

Strain dependence of the optical properties and band gap of transparent conducting BaSnO3 and SrSnO3

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N-type perovskite structure stannates based on BaSnO3 with doping by La and/or Sb, have attracted recent interest as transparent conductors. In analogy with materials like SrTiO3, the perovskite structure suggests the possibility of complex structural distortions under strain, which may then provide for strain tuning of properties. Here, we report calculations of the optical properties and band gaps as a function of strain for BaSnO3 and SrSnO3. We find that these materials behave very differently from perovskites like SrTiO3 in that there is a very strong sensitivity of the properties to volumetric strain, but practically no dependence on other strains. The results are discussed in relation to the s-electron character of the conduction band and simple formulas for the strain dependence of the gap are given.

9177-16, Session 4

Development of transparent and conductive Al doped Zn1-xMgxO thin film by sol-gel process with two-step annealing

Lei Meng, Shinsuke Miyajima, Makoto Konagai, Tokyo Institute of Technology (Japan)

Transparent conducting oxides are one integral part in various optoelectronic devices such as liquid crystal displays, light emitting diodes and thin film solar cells. Al doped ZnO (AZO) thin film is one promising candidate as front TCOs in Si thin film solar cell, because the lower cost than tin doped indium oxides and better resistance to hydrogen plasma than fluorine doped tin oxides in plasma assisted chemical vapor deposition fabrication process. In order to reduce the optical loss in AZO thin film at short wavelength range around 350nm due to low band gap energy of 3.4 eV, development of new TCOs thin film with wider band gap is in urgent demand. In this work, Al doped Zn1-xMgxO (AZMO) thin film was developed by using sol-gel process with two-step annealing. Effect of annealing temperature and atmosphere on structural, optical and electrical properties of thin film was systematically investigated. It was found that first annealing temperature determines film crystallinity and grain size, while second annealing plays a critical role in activating carrier. All of AZMO thin films show a (002) preferential orientation, a surface roughness of about 2 nm and a high transmittance of over 85% in wavelength range from 400nm to 1500 nm. The relevant mechanism was discussed. One low resistivity of 2.1?10-2??cm was achieved with a band gap energy of 3.6 eV. With further reduced resistivity, such AZMO thin film holds great potential to be applied as the transparent conductive layer in Si thin film solar cell.

9177-17, Session 4

High temperature annealed SnO2/Sn-Ag/ITO window electrodes for dye sensitized solar cells

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In this study, a transparent conducting film (TCO) for SnO2/Sn-Ag/ITO glass was designed based on calculation of the film matrix. It was proven that there was higher transmission in the visible regions aided by the transparent heat mirror effect in the NIR region. As per the experimental results, the average transmittances were 77.7%/42.3% in the 400-750/800-1300 nm range for SnO2/9-nm Ag/40-nm ITO glass, and 70.82%/25.2% in the 400-700/800-1300 nm range for SnO2/12-nm Ag/40-nm ITO glass. Although these samples had 4 and 8 ohm/sq of sheet resistance, respectively, the transmittance would decay to 63.1%/27.4% and 67.2%/40.8% as a consequence of the metal clusters of Ag that formed after annealing at 500°C. After this SnO2/1-nm Sn-Ag/ITO glass samples were studied. It was found that Sn3Ag would form on an Ag layer after annealing. The transmittances of SnO2/1-nm Sn- 9-nm Ag/ITO and SnO2/1-nm Sn- 12-nm Ag/ITO glass after 500°C annealing were 77.9%/57.2% and 71.8%/36.8%, respectively. In addition, both of these materials had sheet resistances below the 10 ohm/square. Finally, SnO2/Sn-Ag/ITO glass was successfully fabricated after 500°C annealing to produce the transparent heat mirror design. The transmittance of this material with the transparent heat mirror design was greater than 70% in the spectra of 400-750 nm and less than 40% in the 800-1300 nm range, and the sheet resistance was less than 10 ohm/sq.

9177-18, Session 4

Metal nanowire-graphene composite transparent electrodes

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Silver nanowires with 40 nm widths and copper nanowire with 150 nm were synthesized using low-temperature routes and deposited on top of ultrathin graphene films for use as transparent conductors. A systematic and detailed analysis involving nature of capping agent for the metal nanowires, annealing of films, and pre-treatments of substrates revealed critical conditions necessary for preparing high performance transparent conducting electrodes. The best electrodes show ~75 % transmission and sheet resistance ~10 Ω/?, already comparable to best available transparent electrodes. The metal nanowire-graphene composite electrodes are therefore well suited for fabrication of opto-electronic and electronics devices.

9177-19, Session 4

Transparent conducting electrodes based on narrow, ultra-long copper nanowires and graphene nanocomposites

Zhaozhao Zhu, Trent Mankowski, The Univ. of Arizona (United States); Kaushik Balakrishnan, College of Optical Sciences, The Univ. of Arizona (United States); Farid Touati, Mohieddine Benammar, Qatar Univ. (Qatar); Masud Mansuripur, College of Optical Sciences, The Univ. of Arizona (United States); Charles M. Falco, The Univ. of Arizona (United States)

High aspect ratio copper nanowires with ultralong lengths (up to 200 ?m) and narrow widths (< 50 nm) were synthesized in large quantities using solution based approach and integrated with graphene sheets towards producing transparent conducting electrodes. These transparent electrodes fabricated achieved high %T and have resistances values comparable to existing electrodes. Furthermore, the electrodes show no notable loss of performance under high temperature and humid conditions. The adaptations of such nanomaterials into smooth and ultrathin films lead to potential alternatives for tin-doped indium oxide

(ITO), which can be utilized in a wide range of solar cells, flexible displays and other opto-electronic devices.

9177-20, Session 5

Optimization of hybrid antireflection structure integrating surface texturing and multi-layer interference coating

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The antireflection structure (ARS) for solar cells is categorized to mainly two different techniques, i.e., the surface texturing and the single- or multi-layer interference coating. Although the surface texturing attains a good broadband antireflective performance, the available materials for large-scale and low-cost fabrication is limited. When the material for texturing is different from that used in the solar cell, the occurrence of reflection due to optical mismatching is inevitable. Therefore, it may be worth making use of multi-layer interference coating, in addition to surface texturing, to reduce the effects of such optical mismatching. Here, we consider a novel hybrid ARS, which integrates moth eye texturing and multi-layer coat, for application to organic photovoltaics (OPVs). Using the optical simulation based on the finite-difference time-domain (FDTD) method, we conduct nearly global optimization of the geometric parameters characterizing hybrid ARS. The proposed optimization algorithm consists of two steps: in the first step, we optimize the period and height of moth eye array, in the absence of multi-layer coating. In the second step, we optimize the whole structure of hybrid ARS by using the solution obtained by the first step as the starting search point. The methods of the simple grid search and the Hooke and Jeeves pattern search are used for global and local searches, respectively. The design concept of hybrid ARS is highly beneficial for improving light trapping in the thin active layer of OPVs, and the same concept will be applicable to light trapping for other thin film solar cells.

9177-21, Session 5

Improving thin film amorphous silicon photovoltaic cell efficiency using plasmonic structures

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We performed a systematic optoelectronic numerical study on plasmonic amorphous silicon thin film PV cells using commercial FDTD T-CAD software by optimising silver and gold metal nanoparticles with size (radius) between 10-50 nm. Fine tuning of the nanoparticle size increases the light coupling into the optical modes of the active layer as a result of multiple light scattering and localised surface plasmon resonance, due to the metal nanoparticle size. The simulated device configuration was 1?m wide and consists of 200nm thick n-i-p based amorphous silicon sandwiched between ITO (100nm) front electrode and aluminium (100nm) back electrode. Plasmonic metal nanoparticles of gold or silver are embedded between ITO and glass substrate. The entire device was simulated under AM1.5G solar spectrum between 300-800 nm wavelengths with 10nm spectral resolution. The localised surface plasmon resonance of silver (420nm) and gold (520nm) nanoparticles promotes light coupling which enhances the light trapping in the active layer. Optimisations of device architecture lead to a relative increase of 3.9% and 6.1% in device efficiency for 40nm silver and gold nanoparticles respectively. The optical analysis also suggests reduction of surface reflections by 7.7% and 9.2% and increased light absorption in a-Si:H of 4.9% and 6.1% which results in 14.6% and 15.9% increase in photogeneration rates compared to reference planar device. This computational study suggests that designing new device architectures incorporating plasmonic metal nanoparticle coatings can act as broadband antireflection coatings for thin film PV cell applications and also improves the light management in the cell.

9177-22, Session 5

Light trapping in thin-film solar cells: the role of guided modes

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This paper studies theoretically light trapping in a solar cell configuration consisting of a 50-500 nanometer-thin planar silicon (aSi:H) film with a planar silver back-reflector, and scatterer(s) placed directly on the silicon surface. The usual picture for thicker films is that part of the light incident on the scatterer(s) can be coupled into the silicon film at a continuum of angles above the critical angle for the silicon-air interface, in which case light will be trapped and subsequently absorbed. However, for thin films a more appropriate picture is that of light being coupled into the guided modes of the air-silicon-silver geometry corresponding to discrete angles. The scattering of light into each guided mode, and out-of-plane scattering, will be quantified by the related scattering cross section. It will be shown that scattering-cross-section spectra have sharp resonances near cut-off wavelengths of guided modes, with more closely spaced resonances for thicker films. Total resonant cross sections can easily exceed physical cross sections by a factor 10. This study also includes light trapping due to coupling into the Surface-Plasmon-Polariton mode that exists due to the silver surface. It will be shown that peaks in scattering cross sections can be tuned via the geometry to the appropriate wavelength range where light trapping is advantageous due to weak absorption in the silicon, resulting in an optimum thickness around 250 nanometers. The theoretical calculations include material losses, and both dielectric and metal scatterers are considered. The calculations were carried out with Green's function integral equation methods.

9177-23, Session 5

Light trapping in photonic crystals

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In this work, we quantitatively establish the connection between absorption and DOS, and use this relation to guide photonic crystal absorber designs. To maximize absorption by light trapping, one should aim at maximizing the number of accessible modes supported by an absorber structure. Moreover, we show that to take full advantage of the benefit of the photonic DOS, one need to consider additional issues including accessibility to these photonic states, as well as the overlap of the photonic states with the absorber.

The main aim of our paper is to highlight the unique physics of light trapping in photonic crystals. There are at least two methods to increase absorption by light trapping in photonic crystals. The first method is to enhance the DOS. For relatively narrowband applications, for example, in crystalline silicon solar cells where light trapping is most crucial in the vicinity of the band edge, we can place the van Hove singularities at the desired wavelengths and achieve greater light trapping enhancement than the $4n^2$ limit. We may also stack multiple photonic crystals for combined, and possibly even greater, light trapping enhancement. For broadband applications, for example, to enhance absorption in a weak absorber across the entire visible solar spectrum, engineering (essentially redistributing) the DOS for the greatest benefit is a very difficult non-convex optimization problem. If the refractive index of the absorptive material is lower than its background, then overall DOS enhancement is expected; otherwise, the DOS of the photonic crystal is generally lower than the DOS in the bulk absorber, as in all the simulations in this work where we use a silicon-like material and air. One tradeoff is therefore the refractive index contrast between the higher-index absorber and the lower-index background: on one hand, larger index contrast gives rise to more prominent van Hove singularities; on the other hand, smaller index contrast means less reduction in the overall DOS.

The second method is to improve the coupling between the photonic states and the external radiation modes, in other words, the optical modes supported by the photonic crystal need to be leaky in order to contribute to light trapping. Those modes below the lightline in free space cannot couple to external radiation due to the mismatch of parallel wave vectors. However, one can increase the periodicity of the structure and essentially push more modes above the lightline. We have shown that this approach is very effective by a simple rotation of the photonic crystal lattice. Another method to improve coupling is to roughen the surface or to use a grating, which scatters the parallel wave vectors and helps the external radiation to couple into the modes that are previously inaccessible. We have shown that such a surface grating is achievable by simply varying the radii of dielectric rods in the first layer of the photonic crystal. We can further improve the coupling efficiency by combing the strategies presented above.

9177-24, Session 5

Bilayer structures optimization as antireflective coating for silicon solar cells

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The optimization of a silicon solar cell involves also the design of a proper antireflective coating (AR).

We have considered different bilayer structures. The use of bilayers is oriented to have an antireflective effect on a broader range of wavelengths compared to single film AR. The materials considered include silicon oxide, magnesium fluoride, silicon nitride and titanium oxide. The thickness of each film in each structure has been optimized by theoretical calculations in order to minimize the weighted reflectivity, Rw. This is calculated taking into account the optical reflectivity, the internal quantum efficiency of the silicon solar cell and the solar flux on all the range of wavelengths of interest.

Some of these optimized structures have been realized by e-beam vapor deposition. The improved optical performance of the samples have been verified at the UV-vis-nir spectrophotometer.

9177-25, Session 5

Si nanowire array antireflection layers for ultrathin crystalline Si solar cells

Minji Gwon, Yunae Cho, Dongwook Kim, Ewha Womans Univ. (Korea, Republic of)

We have investigated optical characteristics of 10-um-thick Si wafers with Si nanowire (NW) arrays on the front surface using the finite-difference time-domain (FDTD) simulations (Lumerical FDTD Solutions). We have carried out calculation studies to design optimal Si nanowire array for ultrathin crystalline Si (c-Si) solar cell applications. Optical reflectance, transmission, and absorption spectra were obtained for NW arrays with various diameter and period. The NW array significantly enhanced the absorption, with the aid of resonant guided modes, Fabry-Perot type interference, and diffraction. In addition, the optical spectra in visible wavelength range could be understood based on graded refractive index effect and coupled optical modes between neighboring NWs. Cross-sectional field profiles revealed that the NW diameter and the array period significantly influenced the optical field distributions. These results provide a design guideline for selecting optimal antireflective NW arrays maximizing the optical absorption in the planar absorber rather than in the NWs. Such NWs will increase the photocurrent of the ultrathin c-Si solar cells, while avoiding serious recombination loss at the NWs.

9177-302, Session Plen

The Renaissance of CdTe-based Photovoltaics

William Huber, GE Global Research (United States)

Over the past several years, CdTe-based photovoltaics have undergone a revolution. CdTe is a mature PV technology, spanning more than 55 years. Steady advancements in CdTe module manufacturing, coupled with CdTe's inherent manufacturing simplicity, have driven down the cost of commercial CdTe modules to under $0.55/W at present. Until recently however, CdTe module efficiencies have lagged behind competing technologies. For a decade, CdTe record efficiencies remained dormant, far behind poly Si as well as the competing thin film PV technology, CuInxGa1-xSe2 (CIGS). Over the past several years, CdTe record cell efficiencies have dramatically increased and are nearly at parity with poly Si and CIGS. Given the recent trajectory, CdTe is poised to become the most efficient polycrystalline PV technology in the very near future. This talk will highlight the advantages of CdTe for PV, key advancements in the field and opportunities for further improvements.

9177-26, Session PWed

Effects of steel counter electrode on performances of dye-sensitized solar cells

Jae-Ryung Lee, Young Jun Park, Je Hoon Bak, POSCO (Korea, Republic of)

Thin-film solar cells based on dyesensitized will play an important role because of their high efficiency and cost-reduction potential. TiO2-based dyesensitized thin-film PV technology has came to the performance level competitive against the poly-crystalline Si PV technology. We have improved the efficiency of DSC solar cells to 5.5 % on 25.0 cm? area, which is a new record and exceeds the efficiency of 1-TCO type of dyesensitized solar cells. The presentation will also address with our recent development of hybrid type low cost solar cells as well as flexible steel-based counterelectrode system.

9177-27, Session PWed

Fabrication of ZnS buffer layer for CIGS solar cells by highly deposited rate chemical bath deposition process

Wei-Tse Hsu, Shih-Cheng Chang, Sheng-Wen Chan, Chien-Chih Chiang, Lih-Ping Wang, Chou-Cheng Li, Jen-Chuan Chang, Song-Yeu Tsai, Industrial Technology Research Institute (Taiwan)

CIGS solar cells have shown the conversion efficiency beyond 20%, but the toxic material "CdS" was still used as a n-type buffer layer in the solar cell. Recently, ZnS/CIGS solar cells were developed rapidly and it could also show efficiency as high as 20.9%. But the zinc-based buffer layer has two drawbacks such as low deposition rate and insufficient coverage, which must be met for large mass production. In this study, ZnS buffer layers for CIGS solar cells were prepared by a high rate chemical bath deposition process. In this process, 30 nm ZnS thin film could be prepared within 5 minutes. Following, an extra ZnS thin film prepared by traditional process(5 minutes) was deposited on the as-grown ZnS thin film to passivate the defects. Scanning electronic microscopy and UV–visible–NIR spectrophotometer were employed to characterize the thin film quality. The results hint that the bi-layer thin film has good uniformity, good coverage and high transmittance. The optical bandgap of the as-grown ZnS thin films were measured to be 3.6eV. Besides, the bilayer ZnS/CIGS could show good efficiency without intrinsic ZnO layer. The efficiencies of bilayer-ZnS/CIGS solar cells could reach 10%, which was close to a reference CdS/CIGS solar cell(10.4%). The results hinted that the bilayer ZnS process showed promising potential to get good film quality and high throughput, which could be suitable to mass production for CIGS thin film solar cells.

9178-1, Session 1

Recent developments in luminescent solar concentrators *(Invited Paper)*

Wilfried G. J. H. M. van Sark, Utrecht Univ. (Netherlands)

Full spectrum absorption combined with effective generation and collection of charge carriers is a prerequisite for attaining high efficiency photovoltaic devices, while maintaining cost effectiveness in manufacturing. Spectrum modification using down shifting has been demonstrated in luminescent solar concentrators since the 1970s. These consist of a highly transparent plastic plate, in which luminescent species are dispersed, which absorb incident light and emit light at a red-shifted wavelength, with high quantum efficiency. Material issues have hampered efficiency improvements, in particular re-absorption of light emitted by luminescent species and stability of these species. In this contribution, I will focus on reviewing approaches to minimize re-absorption, which would allow surpassing the 10% luminescent solar concentrator efficiency barrier.

9178-2, Session 1

Singlet fission by novel chromophores in various molecular assemblies *(Invited Paper)*

Justin C. Johnson, Joel N. Schrauben, Joseph Ryerson, National Renewable Energy Lab. (United States); Josef Michl, Univ. of Colorado at Boulder (United States); Arthur J. Nozik, National Renewable Energy Lab. (United States) and Univ. of Colorado (United States)

Singlet fission, a process by which one photoexcited singlet becomes two triplets, has become a topic of intense interest recently as both an intriguing photophysical phenomenon and a route to improved solar photoconversion. Singlet fission is analogous to multiple exciton generation in semiconductor quantum dots and also downconversion by quantum cutting in lanthanides. We have investigated the model chromophores 1,3-diphenylisobenzofuran, a blue-absorbing biradicaloid, and cibalackrot, and indigo derivative, since they possess excited states whose energies and geometries should promote singlet fission while inhibiting competing processes like internal conversion or intersystem crossing. Chromophore design, while important, is only a first step toward demonstrating a practical singlet fission system. The unique modes of intermolecular coupling and environments surrounding the chromophores can have a strong influence on the singlet fission process, thus the way in which molecules are assembled is crucial. We have systematically studied 1,3-diphenylisobenzoran and cibalackrot assembled into covalent dimers, polymers, films of varying crystallinity, bulk crystals, and molecules attached to surfaces. Triplet formation times and yields span decades in these systems, from ~1 ps and 200% in specific polycrystalline films, to greater than 20 ns and negligible triplet yield in weakly coupled dimers. In order to extract useful work from the multiple excitons generated by singlet fission, a scheme for exciton dissociation and charge extraction or photon emission must be developed, and we explore certain design principles within the assemblies to achieve these goals.

9178-3, Session 1

Luminescent down-shifting layers with Eu2+ and Eu3+ doped strontium compound particles for photovoltaics

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In this contribution we discuss luminescent down-shifting (LDS) systems consisting of a polymer matrix filled with phosphor particles. It is an elegant approach to make a use of potentially destructive or otherwise wasted high energy photons and diminish charge carrier losses caused by thermalization in photovoltaics. Sub-micron and micron sized particles of strontium aluminate doped with Eu^{2+} and strontium carbonate doped with Eu^{3+} ions are chosen for the application due to their suitable absorption in UV spectral region. These particles exhibit strong luminescence in visible range between 520 and 650 nm. The systems are carefully designed to meet critical optical requirements such as high transparency in the visible spectrum as well as sufficient absorption of UV light. They are coated on quartz glass substrates (20 x 20 x 1 mm) and can be easily laminated to different kinds of solar cells without any modification to well-established device fabrication processes. Optical characterization further confirms that particles of a few microns in size generate increased light scattering in layers due to the size which is comparable with visible light wavelengths. Dried thick layers of 20 to 100 µm are tested with CIGS and mc-Si cells. The concept of light conversion is experimentally proven. However, optical losses cause a reduction in the overall performance of the tested devices. Possible ways to bring down the amount of light scattering and, thus, to increase optical transmission for the studied system are also addressed and are a subject of future research.

9178-4, Session 2

2D honeycomb semiconductors with Dirac-type electrons and holes: fabrication, electronic structure, and possible applications *(Invited Paper)*

Daniel Vanmaekelbergh, Utrecht Univ. (Netherlands)

The interest in 2-dimensional systems with a honeycomb lattice and related Dirac-type electronic bands has exceeded the prototype graphene. Currently, 2-dimensional atomic and nanoscale systems are extensively investigated in the search for materials with novel electronic properties that can be tailored by geometry. I will show how atomically coherent honeycomb superlattices of rocksalt (PbSe, PbTe) and zincblende (CdSe, CdTe) semiconductors can be obtained by nanocrystal self-assembly, covalent attachment, and subsequent cation exchange. Atomistic and analytical theory predict that these systems combine Dirac-type electronic bands with the beneficial properties of a semiconductor; the systems have a genuine band gap as in a normal 2-D semiconductor, while the valence- and conduction bands transform into Dirac cones. Hence, photo-excitation should generate massless Dirac conduction electrons and valence holes. I will present the first experimental results on the opto-electrical characterisation of PbSe and CdSe honeycomb semiconductors and discuss possible applications.
References: Nano Letters 13, 2317 (2013), PRB 88, 115431 (2013), PRX 4, 011010 (2014).

9178-5, Session 2

Coherence-limited solar power conversion: the fundamental thermodynamic bounds and the consequences for solar rectennas

Jeffrey M. Gordon, Heylal Mashaal, Ben-Gurion Univ. of the Negev (Israel)

Solar rectifying antennas constitute a distinct solar power conversion paradigm where sunlight's spatial coherence is a basic constraining factor. In this presentation, we derive the fundamental thermodynamic limit for coherence-limited blackbody (principally solar) power conversion. Our results represent a natural extension of the eponymous Landsberg limit, originally derived for converters that are not constrained by the radiation's coherence, and are irradiated at maximum flux concentration (i.e., with a view factor of unity to the solar disk). We proceed by first expanding Landsberg's results to arbitrary target irradiance below the maximum allowed value, and then demonstrate how the results are modified when the converter can only process coherent radiation. The results are independent of the specific power conversion mechanism, and hence are valid for diffraction-limited as well as quantum converters (and not just classical heat engines or in the geometric optics regime). The derived upper bounds bode favorably for the potential of rectifying antennas as potentially high-efficiency solar converters.

9178-8, Session 3

Wrinkles and folds as photonics structures in polymer photovoltaics *(Invited Paper)*

Yueh-Lin Loo, Princeton Univ. (United States)

We exploit the elastic instabilities of polymer surfaces under compressive mechanical stress to generate wrinkles and deep folds with prescribed dimensions and at pre-specified coverage over large areas. These wrinkles and deep folds act as photonic structures; they increase light coupling into and trapping within polymer photovoltaics that are subsequently constructed atop such surface structures. Devices on surfaces comprising wrinkles and folds exhibit a 79% increase in the external quantum efficiency (EQE) in the visible compared to analogous devices constructed on flat surfaces. More significantly, we observe an exponential increase in near-infrared light absorption in these devices. In both experiments and in numerical simulations, we find the presence of wrinkles and deep folds to extend the useful range of energy conversion by > 200 nm for model bulk-heterojunctions comprising poly(3-hexylthiophene) and [6,6]-phenyl-C61-butyric acid methyl ester, corresponding to a 600% increase in the EQE in the near-infrared where light is otherwise minimally absorbed. Further numerical simulations indicate this enhanced light coupling and trapping phenomenon to be general; improvements are also predicted for polymer photovoltaics comprising low bandgap polymers. While we demonstrate this concept with polymer photovoltaics, the controlled introduction of compressive stress provides a straightforward and economical route to large-scale patterning of photonic structures for flexible opto-electronics.

9178-9, Session 3

Electrowetting based stationary sun tracking optics

Marco Stefancich, Harry Apostoleris, Carlo Maragliano, Matteo Chiesa, Masdar Institute of Science & Technology (United Arab Emirates)

Mechanically stationary optical tracking of a lightsource (e.g. the sun) can, among other applications, open the path to residential use of concentrator photovoltaics technology with its promise for higher conversion efficiency.

However, for this to happen, Etandue conservation requires some changes in the concentrator optics to combine high concentration with variable acceptance angle. This can be achieved by the use of a system that can be locally switched between a highly reflective to a highly transmissive state.

This can be achieved by electrically moving an index matching liquid inside an array of transparent microchannels, or inside a photonic crystal, thus manipulating the index contrast between the host medium and its content and, consequently, the optical transfer function of the system.

We discuss here the theory behind this optical switch, its possible realization and its use for a mechanically stationary sun tracking system presenting the initial experimental results.

9178-10, Session 3

Highly efficient selective solar absorbers/ emitters based on 2D metallic photonic crystals

Veronika Rinnerbauer, Johannes Kepler Univ. Linz (Austria) and Massachusetts Institute of Technology (United States); Veronika Stelmakh, Yi Xiang Yeng, Yichen Shen, Jay J. Senkevich, John D. Joannopoulos, Marin Soljacic, Ivan Celanovic, Massachusetts Institute of Technology (United States)

Spectrally selective components are critical elements for solid-state thermal-to-electrical energy conversion, such as thermophotovoltaics (TPV), solar-thermophotovoltaic and solar-thermal systems. The key to obtaining high efficiency in this class of high temperature energy conversion is the spectral and angular matching of the radiation properties of an emitter (i.e. sun or thermal radiation source) to those of an absorber (i.e. solar absorber and PV cell). Metallic photonic crystals offer the ability to tailor the photonic density of states and thereby thermal radiation – which allows for the efficient design of such highly selective and highly efficient radiation sources and absorbers.

We demonstrate an integrated double-sided absorber/emitter pair based on 2D PhCs fabricated on a single flat Ta substrate. Both PhCs on absorber and emitter side show broadband low reflectivity at small wavelengths and high reflectivity at long wavelengths, reducing losses due to re-emission at high temperatures, with a sharp cut-off between the two that can be tuned via the PhC geometry. The PhCs are optimized for a solar thermophotovoltaic (STPV) application with high operating temperatures (>1200 K). We demonstrate that at these temperatures, the selective PhC absorber obtains much higher thermal transfer efficiencies, and operates at lower irradiation than blackbody absorbers. Moreover, we propose a solar absorber with a PhC superlattice design achieving broadband high absorptivity and maximum thermal transfer efficiency, and its fabrication by nanoimprint lithography, facilitating precise control of the nanophotonic structures and of the ratio of absorber and emitter area, further reducing losses by re-emission and improving STPV system efficiency.

9178-11, Session 4

Enhanced carrier multiplication in quantum dots through controlled intraband cooling *(Invited Paper)*

Victor I. Klimov, Los Alamos National Lab. (United States)

Carrier multiplication (CM) is a process whereby absorption of a single photon produces multiple electron-hole pairs (excitons). Potentially, it can boost the efficiency of single-junction solar cells to above 40% by increasing the photocurrent. The first spectroscopic observation of efficient CM in PbSe quantum dots, QDs, (Schaller & Klimov, Phys. Rev. Lett., 2004) stimulated fervent activity in this area, including spectroscopic and theoretical studies of multiexciton generation as well as the development of practical devices exploiting CM. This presentation overviews recent progress in understanding CM in quantum-confined nanostructures. Specifically, I will discuss the effect of structural

parameters such as particle size, shape, and composition on CM yields. I will also describe a phenomenological framework for treating CM in terms of two competing energy relaxation pathways, which allows us to rationalize relative variations in CM efficiencies between quantum dots of different compositions, as well as the trends observed during elongation of the nanocrystals (that is, the transition from 0D quantum dots to quasi-1D nanorods). Finally, I will discuss recent efforts on increasing multiexciton production by controlling the competing process of intra-band cooling. This approach can be implemented using, for example, thick-shell PbSe/CdSe quantum dots that demonstrate a four-fold boost in the multiexciton yield compared to standard core-only QDs.

9178-12, Session 4

Exciton transport in colloidal quantum dot solids *(Invited Paper)*

William A. Tisdale, Massachusetts Institute of Technology (United States)

Colloidal quantum dots (QD), also known as semiconductor nanocrystals, are an intriguing material platform for solution-processable optoelectronic devices, such as solar cells, light-emitting diodes, thermoelectric modules, and flexible electronics. In QD thin films, the efficient movement of charge, heat, and excitonic energy is intimately linked to the QD surface chemistry and the amount of structural or energetic disorder in the material. In excitonic solar cells, the efficient diffusion of excitons to charge-separating interfaces is central to device operation. On the other hand, exciton diffusion to quenching interfaces in light-emitting diodes is a process that can limit luminescence efficiency. While the diffusion of singlet and triplet excitons in organic semiconductors has been studied extensively, exciton diffusion in colloidal QD thin films remains largely unexplored. In this talk, I will detail my group's combined experimental and computational efforts to obtain a deeper understanding of excitonic energy transport phenomena in colloidal QD materials. These efforts include spectrally-resolved transient photoluminescence spectroscopy, photoluminescence quenching, time-resolved optical imaging, and kinetic Monte Carlo simulation.

9178-13, Session 4

Recent progress in colloidal quantum dot photovoltaics *(Invited Paper)*

Alexander H. Ip, Edward H. Sargent, Univ. of Toronto (Canada)

Colloidal quantum dots (CQDs) are a unique materials system composed of nanometre scale semiconductor particles synthesized in and processed from solution. This allows the use of CQD inks to be painted onto flexible substrates for rapid, low-cost fabrication of solar cells. Uniquely, CQDs exhibit quantum size effect tunability. This allows the absorption range of CQD films to be tuned, based simply on nanocrystal size, across the entire solar spectrum, including within the infrared range. This makes quantum dots particularly attractive for solar cells in which multijunction approaches utilizing films of various bandgaps can increase photovoltaic efficiencies beyond the Shockley-Queisser limit.

Here we will review the basic concepts, recent advances and future directions in CQD photovoltaics. Since the first reports of CQD based solar cells nearly a decade ago, the power conversion efficiency has increased to over 8%. Progress in materials processing of CQDs has led to reductions in undesirable trap states and contributed to these improvements. Recent developments in doping CQDs have allowed construction of all-CQD quantum junction solar cells. Clever architectures have enhanced device operation and improved absorption of CQD films through photonic and plasmonic effects. Further improvements in this field will draw from materials chemistry, optical enhancements and fundamental physical understanding of CQDs.

9178-14, Session 4

Ultrafast spectroscopy of CuInSeS colloidal quantum dots: Auger recombination, carrier multiplication, and electron transfer

Nikolay S. Makarov, Hunter McDaniel, Istvan Robel, Victor I. Klimov, Los Alamos National Lab. (United States)

Heterojunctions of colloidal semiconductor quantum dots (QDs), and mesoporous titania (mp-TiO_2) are employed in various applications including light-emitting diodes, solar cells, solar fuels, and CO_2 reduction. The efficient separation of electrons and holes at the mp-TiO_2/QD junction is critical for outcompeting various loss mechanisms such as surface trapping.

Here, we investigate optical properties of CuInSeS QDs and QD-sensitized mp-TiO_2 films, which have recently been utilized in solar cells achieving power conversion efficiencies above 5%. We perform systematic transient absorption and time-resolved photoluminescence measurements on QDs with dimensions from 3 to 5 nm to study QD size- and composition-dependence of various excited state processes, including biexciton Auger recombination, carrier multiplication (CM), and electron transfer (ET) to TiO_2. Biexciton decay is found to be similar to that CdSe QDs of the same volume, which supports the assessment of previous reports on the generality of size-dependent trends in Auger recombination in the QDs. CM quantum yields approach 20% indicating that this material could enable photovoltaic efficiencies exceeding the Shockley-Queisser limit. CM threshold though is relatively large, ~3.8 bandgaps, somewhat larger than that in previously reported PbSe and PbS QDs and PbSe quantum rods. Size-dependent ET (20-40 ns time constant) is fairly slow, which highlights the need for efficient suppression of competing nonradiative processes that can be associated, for example, with surface traps in poorly passivated QDs. Yet, high electron extraction efficiency (>95%) can be achieved because in well-passivated CuInSeS quantum dots neutral excitons have significantly longer lifetimes of hundreds of nanoseconds.

9178-15, Session 4

Energy materials: core/shell structural photoelectrodes assembled with quantum dots for solar cells

Jianjun Tian, Shengen Zhang, Univ. of Science and Technology Beijing (China)

In the paper, a photoelectrode made of nanocable core-shell structure of ZnO nanorods (NRs) coated with TiO_2 nanosheets (NSs) was prepared. Anatase TiO_2 NSs with a thickness of ~10 nm and a length of ~100 nm are assembled onto the surface of ZnO NRs via a solvothermal method. The thin shell of TiO_2 shows a remarkable effect on QDSCs by increasing the surface area of ZnO NRs to allow for adsorbing more QDs, which leads to high short current density. Also, the unique material prepared here has an energy barrier that hinders the electrons in the ZnO from being transferred to the electrolyte or QDs, and thus, reduces the charge recombination rate, increases electron lifetime, and enhances open voltage In comparison with the case of ZnO NRs, the short-circuit current density, open-circuit voltage, fill factor, and charge recombination resistance of ZnO/TiO_2 nanocable photoelectrode increase by 3, 44, 48 and 220%, respectively. As a result, a power conversion efficiency of 2.7% in QDSCs with a core-shell structural nanocable photoelectrode has been obtained, which is as much as 230% of that obtained for ZnO NR photoelectrode.

9178-16, Session 5

Plasmonic structures to enhance light-harvesting in organic photovoltaic devices *(Invited Paper)*

Wounjhang Park, Univ. of Colorado at Boulder (United States)

This paper presents a review of recent progress in plasmonic nanostructures for enhanced light harvesting in organic photovoltaic (OPV) devices. Specifically, three subjects will be discussed: combined electrical and optical modeling, plasmonic enhancement of sub-gap absorption, and plasmonic enhancement of frequency conversion. Plasmonic nanostructures often exhibit highly non-uniform optical field profile. The resultant non-uniform carrier generation rates could significantly impact the deice performance. By rigorously modeling both plasmonic fields and carrier transport, we show how non-uniform optical fields affect OPV device performance. We then use the model to develop plasmonic nanostructures for enhanced sub-bandgap absorption. The sub-bandgap absorption has been shown to dramatically improve the energy conversion efficiencies of OPV devices. We used a simple and well-controlled plasmonic grating structure to tune the absorption band. Finally, we investigate the plasmon enhancement of frequency conversion. The nonlinear nature of the frequency conversion process leads to much greater enhancement by the plasmonic fields than the linear processes such as absorption and fluorescence. Our study reveals the mechanism of plasmon enhancement of luminescence upconversion process, providing a solid foundation for advanced engineering.

9178-17, Session 5

Scattering of long wavelengths into thin silicon photovoltaic films by silver nanoparticles

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Nanoparticles and nanostructures with plasmonic resonances are currently being employed to enhance the efficiency of solar cells [1]. Ag stripe arrays have been shown theoretically to enhance the short-circuit current of thin silicon layers [2]. Monolayers of Ag nanoparticles with diameter $d < 300$ nm have shown strong plasmonic resonances when coated in thin polymer layers with thicknesses $< d$ [3]. We study experimentally the diffuse vs. specular scattering from monolayers, sub-monolayer, and bilayer arrays of Ag nanoparticles (spheres and disks with diameters in the range 50 – 300 nm) coated onto the front side of thin (100 nm $< t <$ 500 nm) silicon films deposited on glass and flexible polymer substrates, the latter originating in a roll-to-roll manufacturing process. Ag nanoparticles are held in place and aggregation is prevented with a polymer overcoat. We observe interesting wavelength shifts between maxima in specular and diffuse scattering that depend on particle size and shape, indicating that the nanoparticles substantially modify the scattering into the thin silicon film. Using both simulation and optoelectronic measurements (spectrophotometry, electrical characterization with and without solar simulation), we predict the enhancement of long-wavelength scattering and overall efficiency from thin film silicon and other photovoltaic materials.

[1] H. A. Atwater and A. Polman, Nature Materials 9 (2010) 205.

[2] R. Pala, et. al., Adv. Mats. 21 (2009) 3504.

[3] M. K. Kinnan and G. Chumanov, J. Phys. Chem. C.114 (2010) 1796.

9178-18, Session 5

Plasmonic rear reflectors for thin-film solar cells: design principles from electromagnetic modelling

Claire E. R. Disney, Supriya Pillai, Craig M. Johnson, Martin A. Green, Qi Xu, The Univ. of New South Wales (Australia)

Nanosphere lithography (NSL) is an inexpensive technique for preparing two-dimensional patterns of nanoscale structures. These structures have been shown to enhance optical absorption in thin films such as those used in novel solar cell designs. NSL can be used to produce regular arrays of nanostructures over large areas with tight control over feature size and array periodicity. Arrays can be formed on a variety of substrates, allowing a range of absorber layer materials to be used.

Finite-difference-time-domain simulations using Lumerical software have been used to model a variety of structures in order to optimize their design for use with solar cells. This has been done by analyzing the generation rate within the absorber layer, calculating the idealized short circuit current normalized to the AM1.5 spectrum, and evaluating the spatial distribution of absorption within the structure.

The structures simulated include those where the nanospheres are removed, leaving a regular array of nanoholes in metal; those where the spheres are retained with a cap of metal over them; and those where the spheres are completely embedded in a metal layer. The performance of these structures was also compared to other rear reflector types or no reflector at all. Design parameters investigated include the metal and absorber layer type and thickness, array periodicity and feature size.

A variety of structures has shown promising increases in short-circuit current relative to other rear reflectors. Further simulations have investigated the sensitivity to semi-random variations to feature sizes within an array with similarly promising results.

9178-19, Session 5

Enhancing solar cell efficiency by lenses on the nano- and microscale

Martina Schmid, Phillip Manley, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany)

Plasmonics have found their application in solar cells: scattering, near-field enhancement and coupling into guided modes by metallic nanoparticles can help to improve the efficiency [1]. Large scale solar concentrators have allowed the enhancement of solar irradiation by several hundred times thereby boosting the solar cell efficiency to beyond 44% [2]. But what do the concepts of scattering nanoparticles and concentrating optics have in common?

From metallic nanoparticles we turn to dielectric particles and then make the link to concentrator optics looking at lenses on the mircoscale. The nano- and microlenses are investigated with respect to their interaction with light using 3D simulations with the finite element method solving Maxwell's equations as well as by ray tracing calculations. We find distinct similarities in the enhancement principles and will discuss their application to photovoltaics with a particular focus on Chalcopyrite solar cells. Cu(In,Ga)Se2 solar cells have achieved the highest conversion efficiency amongst polycrystalline thin-film materials [3] and thus provide a profound basis for applying novel concepts at the same time looking towards reduced material consumption of the rare element Indium.

[1] Atwater HA, Polman A, Nature Materials 9, p. 205 (2010)

[2] Sharp, press release http://sharp-world.com/corporate/news/120531.html (2012)

[3] Empa, press release http://www.empa.ch/plugin/template/empa/1/131438/---/l=2 (2013)

9178-20, Session 6

Minority carrier lifetime of thin polycrystalline silicon nanowire films on polycrystalline silicon layer prepared by aluminum-induced crystallization

Tatsuya Yamazaki, Tokyo Institute of Technology (Japan); Shinya Kato, Japan Science and Technology Agency (Japan); Shinsuke Miyajima, Makoto Konagai, Tokyo Institute of Technology (Japan)

The silicon nanowires (SiNWs) film is one of the promising materials for photovoltaic application due to the potential of bandgap engineering and strong optical absorption. However the net surface recombination velocity of SiNWs is very high due to the large surface area. Therefore, the passivation layer which reduces the surface recombination velocity is required for solar cell application of SiNWs films. Conformally-deposited aluminum oxide (Al2O3) by atomic layer deposition (ALD) is suitable for this purpose due to the excellent passivation effect of Al2O3 for crystalline silicon. In this study, we demonstrate minority carrier lifetime measurement of poly-SiNWs films passivated with Al2O3. The poly-SiNWs films were prepared by using solid phase crystallization of amorphous silicon (a-Si) and subsequent metal assisted etching. A polycrystalline silicon template was prepared on a quartz substrate by aluminum induced crystallization (AIC) method. Subsequently, a 1-?m-thick undoped a-Si layer was deposited on the AIC-grown seed layer by RF sputtering. The undoped a-Si layer was crystallized by thermal annealing. Nanowire structure was prepared by metal assisted etching of this polycrystalline silicon layer. The carrier lifetime of bare poly-SiNWs films was unmeasurable due to the very small microwave photoconductance signal, suggesting that surface recombination is very high. On the other hand, the carrier lifetime of Al2O3 post-annealed SiNWs arrays was able to measure and the effective lifetime was found to be 5.76 ?s. This result clearly indicates that ALD- Al2O3 is effective to reduce the carrier recombination at the surface of the poly-SiNWs.

9178-21, Session 6

Influence of substrates on formation of polycrystalline silicon nanowire films

Shinya Kato, Japan Science and Technology Agency (Japan); Tatsuya Yamazaki, Shinsuke Miyajima, Makoto Konagai, Tokyo Institute of Technology (Japan)

There is growing interest in the development of thin film crystalline silicon (c-Si) solar cell. However short circuit current density (Isc) becomes smaller due to the reduction of light absorption for thin film c-Si solar cells. To increase Isc, polycrystalline silicon nanowires (poly-SiNWs) are effective due to its strong light confinement effect. In this study, we investigate the influence of substrates and film deposition techniques on formation of poly-SiNWs films. An undoped amorphous silicon (a-Si) film was deposited on a quartz substrate and a Si wafer (p-type, (100), 2-5 Wcm) by using electron beam evaporation and radio-frequency sputtering. Solid-phase crystallization of the a-Si films were carried out by thermal annealing under forming gas at 900oC for 30 min to form polycrystalline silicon films. These samples were dipped into the solution containing 4.8M HF and 0.001M AgNO3 to form with silver particles on the surface. Subsequently, these samples were chemically etched by using 4.8M HF and 0.15M H2O2 at room temperature. The remaining silver particles were removed by HNO3 etching. The oxide layer on the prepared poly-SiNWs was removed with HF solution. In the case of the electron beam evaporated a-Si on quartz substrates, the formation of poly-SiNWs was not observed and the structure was found to be porous silicon. For the other samples, poly-SiNWs were successfully prepared. These results indicate that substrates and deposition techniques are very important to prepared poly-SiNWs films.

9178-22, Session 6

Effect of tapered shape on performance of silicon nanowire solar cells

Yasuyoshi Kurokawa, Tokyo Institute of Technology (Japan); Shinya Kato, Japan Science and Technology Agency (Japan); Makoto Konagai, Tokyo Institute of Technology (Japan) and Japan Science and Technology Agency (Japan)

The influence of a tapered shape on the performance of SiNW solar cells with the diameter of 1-10 nanometers was investigated using the two-dimensional device simulator with taking bandgap widening owing to the quantum size effect into account. The heterojunction structure of transparent conductive oxide/p-type hydrogenated amorphous silicon oxide/n-type tapered SiNW embedded in SiO2/n-type hydrogenated amorphous silicon/Al electrode was assumed in this calculation. The diameter of the SiNW was changed linearly from the top to the bottom and the length was fixed at 10 um. To introduce the quantum effect into the electrical transport in SiNW solar cells, the Bohm quantum potential (BQP) method was adopted. In this method, we can tune the degree of quantum confinement by varying a proportionality factor (g) of quantum potential.

In the case of g=0, there is little electric field in a neutral region of the tapered SiNW, since the bandgap widening owing to quantum confinement does not occur. On the other hands, strong electric field appeared in the tapered SiNW in the case of g>0. At g=3.7, the bandgap of the SiNW was increased from 1.13 to 4.03 eV with decreasing the diameter of the SiNW from 10 to 1 nm. When there is no electric field in the neutral region and surface recombination velocity (S) on the whole surface of the SiNW increased, open-circuit voltage (Voc) was decreased remarkably. On the other hand, the strong electric field due to quantum confinement suppressed the reduction of Voc regardless of the increase of S. This result suggests that it is possible to reduce the influence of SiNW surface on the performance of the solar cell.

9178-23, Session 6

Fabrication of nano-walls for solar cell application

Yukimi Ichikawa, Hiroshi Tomizawa, Japan Science and Technology Agency (Japan); Shuhei Yoshiba, Masakazu Hirai, Japan Science and Technology Sgency (Japan); Makoto Konagai, Tokyo Institute of Technology (Japan)

We have studied a crystalline Si based tandem solar cell composed of a nano-wall top cell and a conventional p/n junction bottom cell. The effective bandgap of Si increases with decreasing width of the wall by the quantum confinement effect; it is expected that the bandgap increases to 1.5eV or higher when the wall width is narrower than 2nm. Applying these wide bandgap Si to the top cell, we expect higher conversion efficiency. It is, however, very difficult to fabricate such a narrow wall. In this work, we studied how to make nano-walls with a width of several nm by adopting top-down processes.

In the experiment, we used a liquid immersion lithography with ArF laser to make nano-wall patterns on a Si wafer, and obtained line and space patterns with a minimum line width of 50 nm. Then we etched it by a trench etcher to make vertical walls with a height of about 1000 nm. The width of the walls after etching is not narrow enough for the requirement of quantum confinement. Thus, thermal oxidation and oxide etching were repeated to narrow down the width of Si walls. For device application, surface passivation is another important issue. Thermal silicon oxide also works as a support for the nano-walls. Thus at the final step, we left silicon oxide around the walls, and then obtained an array of nano-walls with a width of 1.5-2.0 nm.

We will present the fabrication process of nano-walls in detail, and also some optical properties of the nano-walls such as photoluminescence and reflection.

9178-24, Session 6

Properties of Si/SiO2 superlattice nanodisc array prepared by nanosphere lithography

Takaya Higa, Tokyo Institute of Technology (Japan); Ryousuke Ishikawa, Japan Science and Technology Agency (Japan); Shinsuke Miyajima, Makoto Konagai, Tokyo Institute of Technology (Japan)

We investigated structural and optical properties of amorphous and crystallized silicon based superlattice nanodisc arrays for solar cell applications. Amorphous Si (a-Si)/silicon dioxide (a-SiO2) superlattice was deposited on quartz substrate using radio-frequency reactive sputtering at room temperature. The thickness of the a-SiO2 layer was kept constant at 3 nm. The thickness of the a-Si layer ranged from 1.4 to 8.8 nm. The period of the superlattice ranged from 10 to 200. The transmission electron microscope (TEM) image and the depth profiles of Si and O determined by electron energy-loss spectroscopy (EELS) of a sample clearly show the superlattice structure. Solid-phase crystallization of the amorphous superlattice was carried out by thermal annealing under forming gas for 2 hours at 1000 oC. To form superlattice nanodisc arrays, nanosphere lithography (NSL) was applied for the crystallized superlattice. In the NSL process, silica particles with a 1-um-diameter was employed as an etching mask. The closed packed silica particles were self-assembled by spin-coating on the superlattice surface. By etching of the superlattice with the mask using reactive ion etching (RIE), superlattice nanodisc arrays were successfully prepared. We also found that superlattice with pyramidal or columnar nanostructures can be fabricated by changing etching conditions. The results of optical measurement revealed that nanodisc structure improves the optical absorption in the superlattice. We also compared the optical properties with the simulation results using rigorous coupled wave analysis (RCWA). These obtained results suggest that the nanostructures prepared by NSL are important for optical confinement in the silicon-based superlattice.

9178-25, Session PWed

Enhanced near-infrared response of CdS/CdTe solar cell using Tm3+ and Yb3+ co-doped upconverting glass phosphors

Zhengda Pan, Don Whyte, Steven H. Morgan, Fisk Univ. (United States); Jiaojiao Li, Abdulaziz Alasward, Joseph D. Beach, Colin A. Wolden, Colorado School of Mines (United States)

The sub-bandgap transmission of long wavelength photons results in transmission loss which is a major loss for solar cell with bandgap larger than 1.25 eV. Aiming to reduce the sub-bandgap transmission loss and to overcome the classical efficiency limit of solar cells, Tm3+ and Yb3+ co-doped upconverting (UC) glass phosphors were used to convert near-infrared to visible light incident on a CdS/CdTe solar cell. Current-voltage measurements were performed on the solar cell. A photocurrent enhancement of 31 μA was obtained using the glass phosphor, illuminated by a 980 nm diode at 100 mW. This enhanced response corresponds to external quantum efficiency (EQE) of 0.04 %, which is expected to be increase with improved collection of the UC light. The photo-current observed was proportional to the UC light intensity from the glass UC phosphor. A non-linear relation between the output photo-current and the incident power of the infrared light was observed, similar to the relation between UC intensity and the incident power. UC efficiency of the glass phosphor was calculated using EQE values at both UC wavelength and 980 nm.

9178-27, Session PWed

Development of nanostructured luminophore coating for broadening of solar cell absorption spectrum

Andriy Kryuchyn, Institute for Information Recording (Ukraine); Ievgen V. Beliak, National Taras Shevchenko Univ. of Kyiv (Ukraine)

Design of the solar cells is a hot area of semiconductor physics and material science. One of the major concerns in this area is a substantial shift between the solar radiation spectra and optical absorption spectra of a photoelectric transducer that significantly reduces solar cell efficiency. We propose a concept which based on coating of conventional and cheap photoelectric transducer with a luminophor that transmits longer wavelengths of the sunlight, absorbs shorter wavelengths and converts them to longer ones by the value of the Stocks shift. While photoluminescent light is not collimated and thus losses may reach up to 50% of converted light, it was also proposed to make micropattern formation at photoelectric transducer surface.

We propose synthesizing of specific materials based on composite pyrazoline dyes with addition of polymethylmethacrylate, polystyrene and UV-laquers. It was revealed that synthesized luminophor coating are characterized by sufficiently enough spectral shift (200-400 nm), high quantum yield (near 80%) and stability under circumstances of long term radiation. Further research demonstrated potential of the significant characteristic's improvement by introducing of organic dye molecules in the white zeolite matrix with additional laser annealing at low intensity/ Experimental results have shown that photoluminescent spectrum of pyrazoline dye didn't change shape, bandwidth and amplitude for last 10 years.It was decided that obtained stability is being caused by porous matrix of white zeolite.

Simulation of the solar cell functioning helped to understand physics of the process and simplify problem of microrelief and luminophor optimal parameters search.

9178-28, Session PWed

Photovoltaic properties of copper containing and silver containing diamond like carbon nanocomposites

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Nanoparticles of the group I metals such as silver, gold and copper received significant huge interest of the researchers due to the strong surface plasmon resonance in these materials. Particularly photovoltaic applications of these nanoparticles include possibility to increase light absorption efficiency of the solar cell active layer due to the light scattering and near field effects as well as direct injection of the plasmonic photoelectrons from the nanoparticles to the semiconductor. Stability of the plasmonic nanoparticles can be increased by using core-shell concept and ultra-thin protective layers. Particularly silver nanoparticle containing nanocomposite can be used for such a purpose. Above all diamond like carbon is good candidate for such application due to the chemical stability as well as good combination of the mechanical, optical and electrical properties. It is possible to grow diamond like carbon nanocomposite containing silver, copper or gold nanoparticles. Surface plasmon resonance effect was reported for these nanocomposites.

In present study copper containing and silver containing diamond like carbon (DLC:Cu and DCL:Ag) films were deposited by reactive magnetron sputtering. Direct current magnetron sputtering and high power pulsed magnetron sputtering was used. Structure and composition of films were studied by Raman scattering spectroscopy, X-ray diffractometry, energy dispersive X-ray spectroscopy and atomic force microscopy. Photovoltaic properties at different excitation wavelengths were investigated. Surface enhanced Raman scattering in DLC:Cu and DLC:Ag films was studied as a measure of the plasmonic enhancement of the electric field. Possible relations with structure, chemical composition and optical properties of the nanocomposites were considered.

9179-1, Session 1

The importance of reliability to the SunShot Initiative *(Invited Paper)*

Shubhra Bansal, Rebecca Jones-Albertus, U.S. Dept. of Energy (United States)

The U.S. Department of Energy's SunShot Initiative aims to make the cost of solar power competitive with conventional electricity sources by 2020. To meet this goal, it is estimated that photovoltaic systems must have a lifetime of 30 years with an annual performance degradation rate of 1%. Accordingly, the actual performance and reliability values are important levers in the cost of solar power. For example, if the annual degradation rate is 0.5% instead of 1%, installed system costs can be 7% higher and still meet the SunShot targets. This talk will further examine the influence of performance and reliability on the levelized cost of solar electricity and the goals of the SunShot Initiative.

The SunShot Initiative and Solar Energy Technologies Office invest over $20 million per year in projects focusing on cell performance, standards and reliability at the National Renewable Energy Laboratory, Sandia National Laboratory as well as universities and industry through the PREDICTS Funding Opportunity Announcement. In addition, many other funded projects have components focusing on reliability. An overview of this work will be presented.

9179-2, Session 1

Overview of the activities of the International PV Module Quality Assurance Task Group 3 on humidity, temperature, and voltage *(Invited Paper)*

John H. Wohlgemuth, Michael D. Kempe, Peter Hacke, National Renewable Energy Lab. (United States)

The Photovoltaic (PV) Module Quality Assurance Task Force is an international organization set up to develop tests that go beyond the IEC PV qualification tests to evaluate wear out of PV modules. The Qualification tests are designed to assure minimum performance and safety standards but are limited by the time and costs allowed for testing. These tests must not be so burdensome as to significantly limit the ability of quality PV modules to enter the market. The QA Task Force aims to develop tests that allow for relevant comparisons of different materials and components of modules as well as the whole modules themselves. A long term goal would be to have a set of tests capable of predicting the service live of PV modules. Task group 3 has been focusing on degradation modes and mechanisms associated with heat, humidity, and high voltage. This has included studying potential induced degradation and moisture ingress modeling highlighting the differences between the results of accelerated stress tests (such as damp heat) and the real use environment. Here we highlight the current activities of the group, our philosophical approach, methodology, recent findings, and future planned work.

9179-3, Session 1

Japanese Task Group 8 activities in international PV module quality assurance *(Invited Paper)*

Keiichiro Sakurai, Akihiro Takano, Masaaki Yamamichi, Hiroko Saito, Masahiko Tomita, Akira Terakawa, Hisanobu Yokoyama, Tadashi Obayashi, Keizou Asaoka, Mika Kambe, Hideki Yoshikawa, Michihiro Takayama, Yuna Koizumi, Shuuji Tokuda, Masayoshi Takani, Michio Kondo, Photovoltaic Power Generation Technology Research Association (Japan)

Activities of Japanese Task Group 8 in International PV Module Quality Assurance are conducted by Photovoltaic Power Generation Technology Research Association (PVTEC) in Japan. Japanese Task Group 8 consists of more than 10 members from Japanese national laboratory and companies.

Japanese Task Group 8 has been discussing difference between conventional damp heat test and outdoor exposure test results. Some results using flexible amorphous silicon modules showed that conventional damp heat test could not duplicate some defects observed in real outdoor field tests. One member, Fuji Electric, reported that "Damp heat and current injection tests" could duplicate some sort of defects observed outdoors. It combines damp heat test?85?, RH=95%?and current injection ?forward current, approx. Ipm?into the module. Current injection may introduce electrochemical reactions in the module under damp heat conditions and generate defects observed outdoors.

Japanese Task Group 8 is going to compare "Damp heat and current injection tests", "Damp heat and photo irradiation tests", and "Outdoor exposure tests" under the cooperation with Task Group 8 in U.S.A. Scope, time frame and progress of Japanese Task Group 8 activities are going to be presented.

9179-4, Session 1

Statistical analysis of degradation modes and mechanisms in various thin-film photovoltaic module technologies

Eric Schneller, Narendra S. Shiradkar, Camila L. Pereira, Neelkanth G. Dhere, Univ. of Central Florida (United States)

PV arrays of various thin film modules technologies such as CIGS, amorphous-Si (glass-glass package) and amorphous-Si (flexible package) have been deployed for over 10 years in hot and humid climate at Florida Solar Energy Center. The performance of selected modules from each array was characterized using visual inspection, dark I-V, flasher I-V, electroluminescence and Infrared imaging techniques. Failure modes such as interconnect failure, solder bond failure, corrosion, and delamination were identified. Failure Mode Effects Analysis was carried out on this data to identify the dominant failure modes and mechanisms in each PV module technology.

9179-5, Session 1

Analysis of the degradation and aging of a commercial photovoltaic installation

Alexander Z. Bradley, Babak Hamzavytehrany, William J Gambogi, DuPont (United States)

Simple and accurate methods are needed to monitor and assess photovoltaic (PV) systems. This becomes increasingly important to characterize and understand the value of the system with regard to safety, performance (including seasonal and geographical variations), and upkeep. It is also becoming important for assessing the secondary or resale value of PV systems. We report the results from an analysis of a commercial c-Si PV array owned and operated by DuPont. Our technical assessment consists of remote monitoring and field inspection with visual examination and thermal imaging to create a pareto chart of degradation modes. Degradation modes became evident as electrical, optical, physical or chemical defects developed with system age. This evaluation provided system data and documented key issues regarding safety and performance. A comparison of remote monitoring and site inspection is presented as well as laboratory analysis (nondestructive and destructive test methods) of modules removed from the service environment.

9179-6, Session 1

Comparison of environmental degradation in Hanwha 295 W and SunPower 320 W photovoltaic modules via accelerated lifecycle testing

Kelly Simmons-Potter, Teh Lai, Ryan P. Biggie, Wei-Jie Huang, Barrett G. Potter Jr., The Univ. of Arizona (United States)

The performance of lifecycle degradation testing of photovoltaic (PV) modules enables the prediction of PV performance lifetimes and return-on-investment for installations of PV systems. With a functional lifetime strongly dependent on field conditions, as well as on materials selection and design, an understanding of the relationship between these interrelated issues and the impact on performance degradation is an important factor in system selection, especially as new PV module designs are developed.

The current presentation will compare the results of an investigation of environmental aging effects in two commercially-available, full-sized, poly- and mono-crystalline Si PV modules. Specifically, we will examine accelerated degradation in a Hanwha HSL72P-PA-0-295K polycrystalline Si module with that of a SunPower 320EL-WHT-D monocrystallline Si module. Lifecycle tests were performed using a full-scale environmental chamber equipped with single-sun irradiance capability, temperature and humidity control. Time-dependent, photovoltaic performance (J-V) was evaluated over a recurring, compressed night-day cycle providing monthly solar insolation, temperature, and humidity conditions that were representative of the southwestern United States. The accelerated test corresponded to one year of exposure in a real-time, fielded module. Temperature and humidity maxima and minima used in the study ranged from 3°C, 32% Rh up to 37°C, 56% to simulate winter and summer extremes. Results show divergence from predicted performance, especially in the case of the monocrystalline Si, in which evidence of delamination was apparent within the first few month-cycles of the test. Initial correlations between accelerated test data and field-test data on similarly manufactured modules will also be discussed.

9179-7, Session 1

Outdoor Performance of CIGS Modules in Different Climates

Kristopher Toivola, Paul F. Robusto, Ajay Saproo, Bill Kessler, MiaSolé HT (United States)

Outdoor Product Reliability Testing for Miasole Glass-Glass CIGS Modules in different external environments is an important aspect is determining the overall product durability and quality. Miasole has implemented outdoor testing in Dry and Hot region (Phoenix, Arizona); Hot and Humid (Miami, Florida); Seasonally Cold with Snowfall (Medina, Ohio) and at Miasole Headquarters in San Clara, CA. Miasole used a second party to perform the outdoor testing except in Santa Clara. We will review the details of the test site setup and racking configuration. The On-Site Implementation that was done to monitor the module performance will be discussed. Also the data transfer and management of the data will be discussed and the methodology used in analyzing the data will be presented. The multi-year performance of Miasole modules will be shown in each of the different test regions.

9179-8, Session 2

Numerical simulation of wind flow over a photovoltaic solar panel using RANS equations *(Invited Paper)*

Andre L. T. Rezende, Leandro F. Chaves, Instituto Militar de Engenharia (Brazil); Neelkanth G. Dhere, Univ. of Central Florida (United States)

The aim of this study is the numerical simulation of wind flow over solar photovoltaic panels. At present there are 113 schools in Florida that use similar 10-kW photovoltaic (PV) solar energy systems installeds on their campus. The PV electricity is fed to the grid and reduces the consumption of grid electericity of the schools. Moreover, these schools serve as disaster relief shelters. During hurricanes or other disasters, grid electricity at the shelters may be interupted for a few weeks. The PV electricity can then serve to provide the minimum critical necessities during such periods. Because of strong winds and hurricanes in this region, it is essential to study the effect of flow of wind on photovoltaic panels. Such study can also be useful to design efficient protectors and supports to guard the panels.

Typicals flows phenomena such as vortex shedding and boundary layer separation may influence the distribution of wind load on PV panels. Because of the similar PV system design and construction, the geometry of the solar panel installations and wind conditions would be similar in the PV systems in 113 Florida schools. The wind speed in critical conditions can reach in excess of 55 m/s. This work consists of a steady state and incompressible flow numerical simulation through the Reynolds Averaged Navier-Stokes equations (RANS). The turbulence closure model uses the shear stress transport (SST) k-w. The main results of the simulations are the pressure and velocity fields that are involved in loads that panels are being subjected to.

9179-9, Session 2

Effect of shading on different PV technologies and how to minimize the impact

Yutao Zong, Arizona State Univ. (United States)

No Abstract Available

9179-10, Session 2

Finite element model simulations for studying the impact of shunts on thin film modules

Frank W. Fecher, Bayerisches Zentrum für Angewandte Energieforschung e.V. (Germany) and Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Claudia Buerhop-Lutz, Bayerisches Zentrum für Angewandte Energieforschung e.V. (Germany); Christoph J. Brabec, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Macroscopic defects, like shunts, can lower the output power of thin film photovoltaic modules dramatically. Hence, it is important to understand the electrical influence of those shunts within a module and their impact on the module performance. However, detailed experimental investigations are hardly realizable as controlled productions of those shunts are not trivial.

Therefore, we developed a 2D electrical finite element analysis based model and studied the influence of a shunt on the module performance for different parameters (irradiance, shunt resistance, shunt size and shunt position) [1]. Most remarkable is the performance dependence on the shunt position inside the cell (resulting in a variation of up to 25 % for the shunted cell's contribution to the module power). Further investigations with our model showed that the origin of this position

dependence is caused by “circular” lateral currents that spread over the electrode layers of the neighboring cells.

By these investigations a profound understanding of the shunt’s influence in a thin film module is demonstrated. The results will be helpful for the interpretation of electroluminescence or thermography images, e.g. for predicting the output power and open circuit voltage of thin film modules.

Despite the fact that our simulations were designed for CIGS-modules, all results are qualitative valid for other thin film technologies, like CdTe, a-Si or organic photovoltaics.

[1] F.W. Fecher, A. Pérez Romero, C.J. Brabec, C. Buerhop-Lutz, Influence of a shunt on the electrical behavior in thin film photovoltaic modules - a 2D finite element simulation study, Solar Energy (submitted)

9179-11, Session 2

Effect of shading on the switching of bypass diodes in PV modules

Narendra S. Shiradkar, Eric Schneller, Neelkanth G. Dhere, Univ. of Central Florida (United States); Vivek S. Gade, Jabil Circuit, Inc. (United States)

Bypass diodes are installed in Photovoltaic (PV) modules in order to prevent the application of reverse voltage across the shaded cells in the event of partial shading of the module. Crystalline silicon (c-Si) modules have one bypass diode per 18-20 cells while thin film modules have at most one bypass diode per module. Ideally, bypass diodes are expected to turn on as soon as a current mismatch is detected between various strings of cells inside the module, which typically occurs in the event of partial shading. However, limited information is available on the actual switching characteristics of bypass diodes in field. The presence of hotspots in field deployed c-Si modules despite of working bypass diodes suggests that the diodes may not be turning on whenever necessary. On the other hand, bypass diodes in thin film modules may only turn on in case of rectilinear shadows and may leave the module vulnerable in other types of shading scenarios. This paper presents simulations carried out to study the effect of bypass diode type, shading area and intensity on the switching of bypass diodes in c-Si as well as thin film modules. The simulation results were experimentally verified by measuring the I-V curves of these modules under different shading configurations and bypass diode types.

9179-12, Session 2

Angle of incidence effects on soiled PV modules

Jim Joseph John, Indian Institute of Technology Bombay (India) and Arizona State Univ. (United States); Vidyashree Rajasekar, Sravanthi Boppana, Sai Tatapudi, Govindasamy Tamizhmani, Arizona State Univ. (United States)

The transmission level of the incident light on the photovoltaic (PV) modules depends on the angle of incidence (AOI) and air/superstrate interface. The AOI dependence for the air/glass interface has already been well established. When the glass superstarte is covered by a soil/dust layer, the air/glass interface is altered and hence the AOI dependence will be changed to the air/soil/glass interface. In this work, PV modules retrieved from the field having different dust densities have been measured for the dependence of the AOI curves on the dust densities. It was determined that AOI curve is inversely related to the soil density. The critical AOI for the air/glass interface is about 57 degree and it shifts dramatically as the soil gravimetric density (g/m2) increases. The measured AOI curves were then fitted and validated with the analytical/empirical models reported in the literature.

9179-13, Session 2

Comparison of outdoor-measurement and modeling of the leakage current for potential induced degradation

Michael Köhl, Stephan Hoffmann, Fraunhofer-Institut für Solare Energiesysteme (Germany)

Leakage currents are a necessary but not sufficient indicator for potential induced degradation (PID). The influence of humidity and temperature on the potential induced leakage current has been investigated previously, yielding models for their correlation. Outdoor exposure of modules with high voltage bias in two different climate regions (Freiburg and Canary Island) with monitoring of the climatic data, the module temperatures as well as the leakage currents of the various models were used to evaluate a model for the cumulated leakage charge as function of the climatic parameters and module related parameters.

Combining models for temperature and humidity dependence yields a general model for the leakage current as function of temperature, humidity and voltage, which could be helpful for the outdoor stress estimation:

I = (fprecip *Rain + 1)*Imax /(1+(Imax /c -1)/ exp (Imax ??(rf-a) ? b))

With Imax = U/Ra(358 K) A ??exp [-(Ea / R)?(1/Ttest – 1/358 K)]

Rain is a rain indicator that has the value 1, if it is raining, or otherwise 0.

The integration of the measured leakage current and the comparison with the model is ongoing amount of leakage charge on a day with four hours of rain was 53 times higher in case of module M17 and 29 times higher for module M18 compared to a sunny day. The impact of rain events on the leakage current is very important because of the very good conductivity of water, and has to be taken into account when the progress of PID during outdoor exposure is evaluated for development of appropriate service life tests.

9179-14, Session 3

Research, test, and development activities performed by junction box bypass diode task force # 4 *(Invited Paper)*

Vivek S. Gade, Jabil Circuit, Inc. (United States)

The presentation provides latest update on the activities performed by the task force in the areas such as electrostatic discharge testing and standards, thermal runaway testing and design validation for such testing along with results of field related stress tests. Recommendations on additional tests to be included in the standards for bypass diode related stress testing is also discussed.

9179-15, Session 3

The impact of sodium and potassium incorporation on the degradation of CIGS solar cells

Mirjam Theelen, TNO (Netherlands) and Technische Univ. Delft (Netherlands); Nicolas Barreau, Institut des Matériaux Jean Rouxel (France); Henk Steijvers, Zeger Vroon, TNO (Netherlands); Miro Zeman, Technische Univ. Delft (Netherlands)

The incorporation of sodium and potassium into CIGS leads to enhanced cell performance, but the influence of these alkali on degradation is unclear. Therefore, three types of CIGS cells were prepared with different sodium and potassium contents (high, low and alkali poor) by changing the molybdenum microstructure [1] or adding a SiNx barrier for the alkali poor CIGS. The cells have been degraded in a hybrid damp heat – illumination setup, which allowed continuous in-situ monitoring of the degradation [2].

It was observed that the alkali poor samples had a relatively low initial efficiency, mainly caused by a lower Voc (average 11.4% & 553 mV for alkali free vs 13.2/11.9% & 646/607 mV for low/high alkali content). After 741 hours of degradation, it was observed that the alkali poor cells' efficiency had decreased to 7.8%, while the other cells had average efficiencies as low as 0.6% (low alkali) and 2.5% (high alkali).

In order to better understand the degradation behavior, SIMS measurements were executed on similar samples before and after degradation. It was observed that the sodium had migrated from the CIGS bulk to the CdS/CIGS interface and the ZnO:Al layer. This effect was of course very limited for the alkali poor samples, which is likely linked to the stability of these samples.

Alkali poor CIGS cells are thus much more stable than CIGS containing sodium and potassium.

[1] Bommersbach, Prog. Photovolt: Res. Appl. 21 (2013) 332–343

[2] Theelen, proc. 39th IEEE PVSC (2013)

9179-16, Session 3

Thermal performance of microinverters on dual-axis trackers

Mohammad A. Hossain, Timothy J. Peshek, Yifan Xu, Case Western Reserve Univ. (United States); Liang Ji, Underwriters Labs. Inc. (United States); Alexis Abramson, Roger H. French, Case Western Reserve Univ. (United States)

Time-series insolation, environmental, thermal and power data were analyzed in a statistical analytical approach to identify the thermal performance of microinverters on dual-axis trackers under real world operating condition. This study analyzed 24 microinverters connected to 8 different brands of photovoltaic (PV) modules from July through October 2013 at Solar Durability and Lifetime Extension (SDLE) SunFarm at Case Western Reserve University. Exploratory data analysis shows that the microinverters' temperature is strongly correlated with ambient temperature and PV module temperature, and moderately correlated with irradiance and AC power. Ambient temperature is the dominating factor in low irradiance morning time, where the irradiance is below 60 W/m2. Noontime data analysis reveals the variations of thermal behavior within the same brands of PV modules and microinverters, and suggests that the microinverters thermal trend is more strongly influenced by PV module temperature than AC power. Hierarchical clustering based on Euclidean distance measure principle was applied to noontime microinverters temperature data to group the similarly behaved microinverters. Microinverter temperature clustering shows that the clustering groups are more strongly influenced by PV module temperature than AC power. A linear regression model has been developed based on ambient temperature, PV module temperature, irradiance and AC power data to predict the microinverters temperature connected to different brands PV modules on dual-axis trackers. The difference between actual microinverter and predicted microinverter temperature lies between 0.4°C to 1.6°C at 95% confidence interval.

9179-17, Session 3

The influence of water and atmospheric gases on the degradation of aluminum doped zinc oxide layers

Mirjam Theelen, TNO (Netherlands) and Technische Univ. Delft (Netherlands); Zeger Vroon, TNO (Netherlands); Nicolas Barreau, Institut des Matériaux Jean Rouxel (France); Miro Zeman, Technische Univ. Delft (Netherlands)

Aluminum doped zinc oxide (ZnO:Al) is used in among thin film solar cells, because of its low price, high transparency and conductivity. However, it is known that contact with water leads to decreased transparency and/or conductivity.

We have studied the impact of water and atmospheric gases on the degradation of ZnO:Al.

In order to accelerate the degradation, ZnO:Al samples were exposed to 'damp heat' (85oC/85% relative humidity), to atmospheric gases air, carbon dioxide (CO2), oxygen and nitrogen and to water purged with these gases. The optical, electrical and structural characteristics were analyzed before, during and after degradation.

Damp heat exposure led to decreased mobility and thus conductivity due to increased potential barriers at the grain boundaries.

With the gas/water experiments, we showed that the driving forces behind ZnO:Al degradation is the combined presence of water and CO2, while those species individually barely lead to degradation: exposure to water without CO2 results in a small decrease in mobility, associated with slow diffusion of water down the grain boundaries, possibly forming Zn(OH)2. When CO2 was also present, the optical and electrical properties of ZnO:Al deteriorated very quickly, while a large increase of hydroxide and carbon was observed by SIMS depth profiling. We propose the formation of Zn5(OH)6(CO3)2. We showed that the impact of nitrogen and oxygen on ZnO:Al degradation is very small.

This study can help the optimization of barrier coatings, which should not only function as a water barrier, since porosity for CO2 should be taken into account as well.

9179-18, Session 4

Quantifying PV module microclimates, and translation into accelerated weathering protocols *(Invited Paper)*

Nancy Phillips, David M. Burns, 3M Co. (United States); Kurt P. Scott, Atlas Material Testing Technology (United States)

Long term reliability is not well addressed by current standards for PV modules or components, and developing accelerated stress protocols and test methods to address the wear out of key components is an active area of effort. A first step is to define the actual stresses placed on the module components in various mounting configurations and environments.

In this paper, we address the microclimate issue with the utilization of real world data from hot/dry, hot/wet, and temperate environments, with subsequent analysis to translate the microclimate data into a portfolio of practical weathering machine settings.

9179-19, Session 4

Investigation of the cross-linking of EVA using photoluminescence spectroscopy *(Invited Paper)*

Beate Röder, Rojonirina M. Ralaiarisoa, Jan C. Schlothauer, Humboldt-Univ. zu Berlin (Germany)

EVA foils with different degrees of crosslinking have been investigated using photoluminescence spectroscopy. The luminescence intensity is found to increase monotonously with the degree of crosslinking. The principal component analysis (PCA) is used to investigate whether further information beyond the luminescence intensity is contained in the spectra which may ultimately enhance the precision of crosslinking degree identification. The PCA results show a visible distinction of the different degrees of crosslinking, ordered along the PC1 axis. The data points of the 0%- sample are densely gathered and clearly apart from the data points of the other samples. These latter are more widely distributed. Although the samples with different cross linking degree are distinguishable. Applying a linear correlation between the intensity of the spectral peak at 450 nm, the degree of crosslinking for the EVA investigated here can be determined with an error of about 2% absolute and 12% relative. Enhanced discrimination can be gathered applying to the PCA results the Naive Bayes Classification.

9179-20, Session 4

Predicting edge seal field performance from accelerated testing

Kedar Y. Hardikar, MiaSolé (United States); Daniel J. Vitkavage, Lam Research Corp. (United States); Ajay Saproo, Todd A. Krajewski, MiaSolé (United States)

Degradation in performance of a PV module attributable to moisture ingress has received significant attention in PV reliability research. Assessment of field performance of PV modules against moisture ingress through product-level testing in temperature-humidity control chambers poses challenges. Development of a meaningful acceleration factor model is challenging due to different rates of degradation of components embedded in a PV module, when exposed to moisture. Test results are typically a convolution of moisture barrier performance of the edge seal and degradation of laminated components when exposed to moisture. It is desirable to have an alternate method by which moisture barrier performance of the edge seal in its end product form can be assessed in any given field conditions, independent of particular cell design. In this work, a relatively inexpensive test technique was developed to test the edge seal in its end product form in a manner that is decoupled from other components of the PV module. A theoretical framework was developed to assess moisture barrier performance of edge seal with desiccants subjected to different conditions. This framework enables the analysis of test results from accelerated tests and prediction of the field performance of the edge seal. Results from this study lead to the conclusion that the edge seal on certain Miasole glass-glass modules studied is effective for the most aggressive weather conditions examined, beyond the intended service lifetimes.

9179-21, Session 4

Effect of UV Aging on Degradation of Ethylene-vinyl Acetate (EVA) as Encapsulant in Photovoltaic (PV) Modules

Amir Badiee, Ricky D. Wildman, Ian A. Ashcroft, The Univ. of Nottingham (United Kingdom)

A lifetime of 20-30 years is generally regarded as a necessary for photovoltaic modules to achieve economic break even. As a consequence, understanding how to improve the durability and reliability of the modules is becoming a necessity. Photovoltaic modules are exposed to extremely harsh conditions of heat, humidity, and ultraviolet (UV) radiation which affect the properties of the encapsulant material and cause yellowing, delamination and degradation of the material, which knock on effects on the performance and the long-term reliability of photovoltaic modules. This study addresses the impact of UV on the properties and adhesion strength of Ethylene-vinyl Acetate (EVA). Fourier Transform Infrared Spectroscopy in Attenuated Total Reflectance (FTIR-ATR) mode was performed on aged samples, coupled with peel tests on Glass-EVA-back sheet samples. The samples were exposed to UV light from a xenon lamp at 0.68 W/m2 @ 340 nm with exposure up to 1000 hours. The FTIR-ATR measurement shows significant changes in the absorption at 1740 cm-1, 1720 cm-1 and 910 cm-1 which correspond to acetate, carboxylic acid and vinyl group respectively. It is shown that the UV exposure is the most significant aging factor. The rate of the photooxidation of EVA is compared by measuring the changes of absorbance at 1718 cm-1 with the UV irradiation time. The results of the peeling test show a decrease in adhesion strength of EVA as a result of UV aging.

9179-22, Session 4

Optical properties of PV backsheets: key indicators of module performance and durability

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Polymeric backsheets are an important component affecting the performance and durability of photovoltaic modules. The optical properties of the backsheet should be considered in the design and performance of a photovoltaic module and the stability and durability of optical properties have an impact on power, safety and appearance. We collect data on reflectance, color, yellowness, transmittance and visual appearance initially, after durability testing and then compare these results with those from outdoor exposure. Changes in optical properties in fielded modules and accelerated durability testing are compared. IR spectroscopy is used to better understand chemical composition and changes to materials in the backsheet. This analysis is conducted on various backsheet materials in accelerated durability testing and compared to outdoor performance to better understand the relevant chemical changes and associated degradation mechanisms. The connection between optical properties and chemical changes is discussed.

9179-23, Session 4

Device to analyze leakage current pathways in photovoltaic modules in real-time

Neelkanth G. Dhere, Narendra S. Shiradkar, Eric Schneller, Univ. of Central Florida (United States)

High voltages used in PV systems especially those deployed in the hot and humid climate, have been identified as a contributing factor in long-term performance degradation of the PV system. This performance degradation is attributed to the high voltage between the cell circuit and the module frame. The Florida Solar Energy Center has pioneered the study of system voltage induced degradation also known as potential induced degradation (PID) in the hot a humid climate. Until now, studies have consisted of applying a high voltage between the cell circuit and module frame and measuring the total leakage current flowing through the module packaging materials. Since there are multiple leakage current pathways in the module, this single measurement has not been sufficient to understand the contribution of each leakage path to the total leakage current. It is well known that the choice of packaging materials, including the front glass, encapsulant and back sheet, has a significant effect on the magnitude of the leakage current, but their specific effect on each leakage pathway was not apparent. The results of a device used to measure the impedance of each path in real time are presented, so as to elucidate the effect of packaging materials and their configuration on the leakage current. This information will be useful in minimizing the system voltage induced degradation.

9179-24, Session 4

Chemical depth profiling of photovoltaic backsheets after accelerated laboratory weathering

Chiao-Chi Lin, Peter J Krommenhoek, Stephanie S Watson, Xiaohong Gu, National Institute of Standards and Technology (United States)

Polymeric multilayer backsheet provides protection for the backside of photovoltaic (PV) module from the damages of moisture and ultraviolet (UV). Due to the nature of multilayer, certain materials properties characterizations of each layer after aging in a multilayer backsheet could only be followed from its cross-section parallel to the backsheet thickness direction. In this study, commercial PPE backsheet films were aged on the NIST SPHERE (simulated Photodegradation via High Energy Radiant Exposure) with UV radiation under accelerated weathering conditions of 85°C and different relative humidity (R.H.) of 5 % R.H. (low) and 60 % R.H. (high). Cryo-mcrotome was used to obtain cross-sectional PPE samples with a flat surface parallel to thickness direction, and chemical depth profiling of multilayers was conducted by Raman microscope mapping. AFM quantum nanomechanical mapping technique was used complementarily for cross-sectional imaging. The results revealed that the PPE backsheet films were comprised of five main layers, including pigmented-PET, core PET, EVA, pigmented-EVA and another EVA, along with their interfaces. The UV degradation on the outer pigmented PET layers was clearly observed on the PPE films. The damages of UV and moisture were mostly confined and blocked by the pigmented-PET layer regardless of low or high R.H. The high R.H. exposed pigmented-PET/PET layers showed more significant deterioration caused by hydrolysis comparing with low R.H. Due to PET/EVA interface degradation in high R.H, there was minor moisture damage near the PET/EVA interface in the PET core layer. It was found moisture deteriorated EVA/pigmented-EVA/EVA layers dramatically, and the moisture ingress in EVA layers and their interfaces were significant. Based on the results of accelerated weathering, this study brings new understanding to the mechanisms of failure observed in polymeric multilayer backsheets during field exposure.

9179-25, Session 5

Junction box wiring and connector durability issues in photovoltaic modules *(Invited Paper)*

Juris P. Kalejs, American Capital Energy, Inc. (United States)

We report here on Photovoltaic (PV) module durability issues associated with junction boxes which are under study in Task 10 of the Module Quality Assurance (QA) Program at NREL. A number of failure modes are being identified in junction boxes in PV arrays in the field which have less than 5 years outdoor operation. Observed failure modes include melted contacts and plastic walls in the junction boxes, separated external connectors and broken latches. Standard IEC and UL tests for modules are designed to expose early mortality failures due to materials selection and design in the assembled module and their impact on performance and safety. Test standards for individual junction box components, when not part of a PV module, are still in development. We will give an overview of the reported field failures associated with junction boxes, and examine standard development as it may impact on testing for durability of junction box components over a 25 year life.

9179-26, Session 5

Above 3000 h outdoor stability analysis of organic solar cells applying water-based V2O5 hole transport layer

Gerardo Teran-Escobar, Raphael K. Arfaoui, Anderson de Souza Lima, Monica Lira-Cantu, Institut Català de Nanotecnologia (Spain) and Consejo Superior de Investigaciones Científcas (Spain)

We have synthesized a water-based V2O5 hydrate which was applied as hole transport layer, HTL, in organic solar cells, OSCs. The V2O5 is processed from a water-based solution of sodium metavanadate in air, resulting in a final thin film with a V2O5•0.5H2O formula. Inverted and normal configuration OSCs were prepared applying Ag back metal electrodes in both cases. Outdoor stability analyses showed T80 even after 1000 h of testing. The stability for the normal configuration OSC was better while the inverted configuration required the use of a UV filter in order to reach comparable response. The initial 20 % loss observed after the first 1000 h was attributed to interalyer mixing of the semiconductor oxides with the active layer, as revealed by depth profile Tof-SIMS analyses of the devices. The V2O5•nH2O thin film was also treated at different temperatures (120 °C, 240° C and 350 °C) and we present here the initial 3000 h stability of outdoor analyses which shows high dependency of the temperature treatment of the V2O5 layer.

9179-27, Session 5

Combined-environment influence on microcrack evolution in mono-crystalline silicon

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Microcracking, initiated during the processing of Si wafer materials for photovoltaic module production, is a significant contributor to performance degradation with time. Environmental conditions (stress state, chemistry) at the crack tip, have the potential to significantly influence crack propagation rate. Moreover, field-based degradation in encapsulant or backsheet materials and seals can produce time-dependent variations in internal module environment, coupling these degradation modes. A physics and chemistry-based understanding of correlations between environmental conditions and crack propagation characteristics would allow the assessment of this failure mode in the context of module degradation models that could assess performance changes under arbitrary environments.

The present work analyzes microcrack morphology evolution in p-type mono-crystalline Si wafers (280 micron thickness) subjected to static stress conditions under a range of temperatures and relative humidities. A microindenter is used to nucleate microcracks that are then subjected to a static bending tensile stress at the indentation surface of approximately 110 MPa via a custom-designed four-point bend apparatus capable of testing multiple specimens simultaneously. A suite of specimens is subjected to 25 C, 30% RH and 40 C, 70% RH conditions in a controlled environment chamber for up to 128 hours. Acceleration of microcrack propagation in the latter set of specimens is observed via scanning electron microscopy. These early results indicate the impact of local environment on microcrack development and the potential for “stress corrosion” behavior. Subsequent efforts focusing on an analysis of local surface chemistries and more varied environmental conditions and chemistries are now underway.

9179-28, Session 6

Overview of PV module manufacturing quality management system *(Invited Paper)*

Govind Ramu, SunPower Corp. (United States)

A quality management system for PV module production is one of the key elements to secure the long-term reliability of PV modules. This paper describes the key requirements for quality management systems

for PV module manufacturers to produce PV modules which secure the consistency of the design, production and product warranty.

Key requirements in the proposed standard include:

1) Focus on the organization's control of the PV module's design to align the expected lifetime with its relationship to the organization's warranty. Warranty claims must be addressed by product and process design or by financial means.

2) A product realization that includes appropriate certification (e.g. IEC qualification, including both type approval and safety testing), a design lifetime that enables compliance with warranty, and recycling provisions

3) Requirement to improve product traceability through the entire supply and delivery chain to enact positive control of the product for recalls and warranty claims.

4) An ongoing, periodic monitoring program to ensure consistency of aspects of manufacturing that may affect safety, performance, and reliability.

5) Special processes such as control of solder connections, safety tests and assignment of PV module power rating with allowed tolerance.

6) Resources to maintain the product warranty system

7) An electrostatic discharge (ESD) safe environment program, as required for raw material storage, processing, and assembly areas

8) Previous failure information incorporated into the requirements of the QMS

9) A method for selection of vendors that can provide quality materials or products

10) Incoming inspections of materials and sub assemblies

11) Routine tests on 100% of product to ensure consistency of initial quality

12) Manufacturing feasibility at the necessary scale, including risk analysis.

Control plan for solar simulators and how they are used in the performance rating of modules.

14) Use appropriate statistical tools and statistically significant sample sizes to make decisions that affect quality of process and products at all stages of the lifecycle.

15) Use of error proofing, Statistical process Control, control plan, Failure mode effects analysis, and 8 Discipline methodology to build PV modules with consistent quality and reliability.

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9179-30, Session 6

A novel combined micro- and electro-luminescence characterization platform for PV materials and devices

Francis Ndi, Eric Teboul, HORIBA Scientific (United States)

Non destructive techniques are always an appealing option for characterizing PV materials and devices because they maintain the integrity of the material or device and therefore provide information about its functioning in its natural state without possible introduction of contaminants or other extrinsic effects. Of the available techniques, Photoluminescence and Electroluminescence are two of the popular optical methods for characterizing such devices.

In this paper we present results and describe a novel flexible microspectrometer set up that measures both micro-photoluminescence and electroluminescence from PV materials and devices on the same platform. Its unique design provides a direct coupling of the microscope excitation and emission collection head to the spectrometer providing extremely high throughputs - an attribute that is desirable when dealing with experimental materials and devices that tend to have low emission efficiencies. This platform also offers the flexibility to use different lasers for PL excitation and a luminescence measurement range of 200nm-1600nm and beyond. Furthermore the same platform can be conveniently used for cryostatic measurements for low temperature defect characterization and failure mode analysis.

In the past such measurements have been carried out using a modified imaging microscope couple to a spectrometer either by a fiber or some other means. The problem with this approach is that the microscope is an imaging device often optimized for imaging in the visible range of the spectrum. The optics that are used to correct image aberrations often get in the way of spectroscopy. The system here described solves this problem.

9179-31, Session 6

The vital role of manufacturing quality in the reliability of PV modules

Peter Rusch, SolarBuyer, LLC (United States)

The PV industry has never questioned the importance of design and material quality for the reliability and safety of PV modules. International standards developed by IEC and UL have been used for many years to evaluate the basic design quality of modules.

However, re-developing tests designed to asses design or material quality do not take into account the influence of day to day manufacturing quality on module reliability and performance. The financial crisis in October 2008 was followed by a drastic reduction in the price of PV modules in 2009 and 2010.

At the same time China was investing heavily in manufacturing capacity on the back of huge demand from Germany and Spain. China rapidly became the world's No.1 producer of solar modules. While China was in the midst of rapid expansion and dramatic cost-cuts, little or no attention was paid to manufacturing quality.

To address the lack of objective information about manufacturing quality, SolarBuyer established the industry's first independent technical due diligence structure for PV module manufacturers funded exclusively by investors and buyers. The database has grown to cover over 65 mainstream module manufacturers.

This work has highlighted that manufacturing quality is not consistent among manufacturers, and that quality often bears little correlation to the manufacturers' size or public perception of the brand. It also showed that the proliferation in types of materials and manufacturing methods used by manufacturers has been rapid and vast.

9179-32, Session 6

A review of manufacturing metrology for improved reliability of silicon photovoltaic modules

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Manufacturing Consortium (United States) and CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

The reliability and durability of crystalline silicon (c-Si) photovoltaic (PV) modules is dependent on the manufacturing materials and processes used by the entire supply chain. In this work, we review known failure modes and degradation mechanisms induced during wafer production, cell manufacturing and module manufacturing, and we investigate areas where metrology can be used to improve the reliability and durability by eliminating the probability of such failures occurring. This work is the culmination of a one-year collaboration between the U.S. Photovoltaic Manufacturing Consortium, University of Central Florida, National Renewable Energy Laboratory and DuPont.

Conference 9180: Laser Processing and Fabrication for Solar, Displays, and Optoelectronic Devices III

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9180-1, Session 1

Overview of laser processing in solar cell fabrication *(Invited Paper)*

Neelkanth G. Dhere, Eric Schneller, Univ. of Central Florida (United States); Aravinda Kar, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

This paper will provide an overview of various laser processing techniques used in the fabrication of solar cells. There are numerous applications of lasers that vary based on type of semiconductor used for the cell and the cell architecture, including laser doping, annealing, patterning, drilling and welding. For thin-film polycrystalline semiconductors such as CdTe and Cu(InGa)(SeS)2 laser annealing has been identified as a potential route to high quality devices. Also for thin-film solar cell technologies, including amorphous-silicon, laser patterning has been widely adopted in industrial processing for implementing monolithic interconnections and performing edge isolation. For silicon wafer based technologies there are a number of promising laser processing techniques, however most of these techniques are still in the development stages and are not yet incorporated into industrial production lines. These techniques that represent the next generation of high-efficiency crystalline silicon devices, include laser-fired contacts, laser doping of selective emitters, laser drilling for “wrap-through” device structures, and laser grooved buried contacts. This paper will present a review of each technique, the specific processing applications and the current state of development.

9180-2, Session 1

The role of lasers in the display manufacturing industry *(Invited Paper)*

Gyoowan Han, Alexander Voronov, SAMSUNG SDI Co., Ltd. (Korea, Republic of)

No Abstract Available

9180-3, Session 1

Laser processing of glass for consumer electronics: opportunities and challenges *(Invited Paper)*

Anping Liu, Corning Incorporated (United States)

Laser processing has demonstrated great capabilities for processing the flat panel display glass, strengthened glass, and flexible glass for consumer electronics. In this paper, a variety of laser processing techniques and their applications are discussed. The techniques include glass cutting, drilling, and surface modification. To assess each technique, a matrix of criteria, such as speed, surface quality, strength, and process stability is proposed. Based on the matrix, future needs for laser processing of glass are outlined.

9180-4, Session 1

Laser microprocessing technologies for automotive, flexible electronics, and solar energy sectors *(Invited Paper)*

Suwas Nikumb, National Research Council Canada (Canada); Ravi N. Bathe, International Advanced Research Ctr. for Powder Metallurgy and New Materials (India); George K. Knopf, Western Univ. Canada (Canada)

Laser micro processing technologies offer an important tool to fulfill the needs of many industrial sectors. In particular, there is growing interest in applications of these processes in the manufacturing areas such as printable electronics, solar energy panels and automotive parts fabrication. The technology is primarily driven by our understanding of the fundamental laser-material interaction, process control strategies and the advancement of significant know-how over the past few years. The wide-ranging operating parameters available with respect to power, pulse width variation, beam quality, higher repetition rates as well as precise control of the energy deposition through programmable pulse shaping technologies, enables pre-defined material removal, selective scribing of individual layer within a stacked multi-layer thin film structure, texturing of material surfaces as well as precise introduction of heat into the material to monitor its characteristic properties are a few examples. In this presentation, research results in the area of laser surface texturing of metals for added hydrodynamic lubricity to reduce friction, processing of ink-jet printed graphene oxide for flexible printed electronic circuit fabrication and scribing of multi-layer thin films for the development of photovoltaic CuInGaSe2 (CIGS) interconnects for solar panel devices will be discussed.

9180-5, Session 2

Influence of surface modification by laser beam interference ablation on characteristics of p-Si solar cells

Simonas Indrisiunas, Bogdan Voisiat, Alfonsas Reza, Irena Simkiene, Regina Mazeikiene, Algirdas Selskis, Gediminas Raciukaitis, Ctr. for Physical Sciences and Technology (Lithuania)

Recently, a lot of attention is paid how to increase the solar energy coupling within the active media of a solar cell. The promising mean is the use of photonic crystal structures to couple and localize the solar radiation. We present the results of novel Laser Beam Interference Ablation technique for surface modification of commercial poly-Si solar cells. This technique gives the opportunity of making high resolution structures with the feature size lower then the laser wavelength on the large surface area with only a single laser pulse.

Additional features on the cell surface with the size comparable with the wavelength of visible light affect light propagation in close vicinity to the cell surface. Therefore, diffuse reflection of the textured cells versus the number of laser pulses per exposure area was examined in details. Laser modified solar cells were characterized by scanning electron microscopy, optical and Raman spectroscopy as well as photo-electrically. The structuring of solar cells surface reduced the reflectance of the light up to 14%. Most of those modifications were related with modification in the anti-reflecting passivation layer of SiNx. Simulations on complex light scattering structures provide good agreement with experimental data. Optimization of laser texturing regime provides means to increase light coupling and preserve photo-electrical properties of solar cells. We discuss the influence of the laser process parameters on optical properties of the Si polycrystalline solar cells.

9180-6, Session 2

Laser doping of germanium for photodetector applications

Keye Sun, Yiliang Bao, Mool C. Gupta, Univ. of Virginia (United States)

A method of doping germanium using 1064 nm pulsed fiber laser was

demonstrated. The secondary ion mass spectrometry (SIMS) showed a p-n junction of 800 nm deep with a peak phosphorus concentration of 2?1019 cm-3. Germanium photodiodes were fabricated on the laser-doped p-n junctions. Low bulk and surface leakage values were obtained which were comparable to diodes fabricated by rapid thermal diffusion. Laser doping allows low thermal budget, minimization of surface desorption and selective doping without requiring photolithography. Laser doping was shown to be an effective method for fabrication of electronic and optoelectronic devices.

9180-7, Session 2

Formation of periodic structures on silicon by laser beam interference ablation technique for light control in solar cells

Bogdan Voisiat, Simonas Indrisiunas, Rasa Suzanoviciene, Irena Simkiene, Gediminas Raciukaitis, Ctr. for Physical Sciences and Technology (Lithuania)

Silicon remains as the main material used in solar cell production, because of its low cost, abundance in nature and well-established technologies. However, it reflects considerable part of light due to its high refraction index. Light harvesting pays an important role for further progress to high-efficient solar cells. Texturing of the substrate surface is an efficient method to enhance the light absorption leading to the higher solar-to-electricity conversion efficiency in crystalline silicon solar cells. We present the novel method for silicon surface texturing using the direct laser beam interference ablation in addition with selective chemical etching. This technique enables production of high aspect ration structures on a large surface area with just a single laser exposure. Characterization of laser textured surfaces was performed using SEM, Raman spectroscopy and absorption and reflection measurements. Theoretical simulation of light interaction with such structures was conducted in parallel and was used to adjust laser process for more efficient light harvesting.

9180-8, Session 2

New strategies in laser processing of TCOs for light management improvement in thin-film silicon solar cells *(Invited Paper)*

Sara Lauzurica, Isabel Sánchez-Aniorte, Miguel Morales, Carlos Molpeceres, Univ. Politécnica de Madrid (Spain); Marta Lluscà, Julian López-Vidrier, Sergi Hernández, Joan Bertomeu, Univ. de Barcelona (Spain)

Light confinement strategies in thin-film silicon solar cells play a crucial role in the performance of the devices. One way to reduce these optical losses is the texturing of the transparent conductive oxide (TCO) acting as front contact. On the other hand other losses arise from the mismatch between the incident light spectrum and the spectral properties of the absorbent material. This implies that low energy photons (below the bandgap value) are not absorbed, and therefore can not generate photocurrent. Upconversion techniques, in which two sub-bandgap photons are combined to give one photon with a better matching with the bandgap, has been proposed to overcome this problem.

In particular this work studies two strategies to improve light management in thin film silicon solar cells using laser technology. The first one addresses the problem of TCO surface texturing using fully commercial fast and ultrafast solid state laser sources. In particular AZO and ITO samples has been laser processed and the results has been optically evaluated measuring the haze factor of the treated samples. A comparison of the experimental results with those obtained through numerical modelling of the optical behaviour can lead to a full optimization of the morphological characteristics of the laser treated surface. On the other hand, laser annealing experiments of TCOs doped with rare earth ions are presented as a potential process to produce layers with upconversion properties, opening the possibility of its potential use in high efficiency solar cells.

9180-22, Session 2

Near-field assisted nanoscale patterning for improved absorption in thin film silicon solar cell

Vadakke M Murukeshan, Prabhathan Patinharekandy, Sidharthan Raghuraman, Nanyang Technological Univ. (Singapore)

Optics technology that focuses on energy sector has in the recent past seen the impact of nanoscale patterning, a challenging trend to achieve smaller features or devices with micro- or nano-scale features. This demands automatically the need for achieving much smaller features beyond the forecasted sub- 30nm fabrication methodologies and hence the push for smaller dimension has posed many challenges. In this context, a new branch of near- field optical concepts, such as evanescent wave and plasmonics, for improving patterning resolution has started developing which have been receiving considerable attention for its ability to produce high density sub-wavelength features. The most significant applications of these fundamental physics concepts have been in the applied engineering problems such as improved broad band light absorption thin silicon solar cells. The absorbance of near band gap light is small and hence structuring of thin film solar cell is very important for increasing the absorbance by light trapping. This presentation will cover the above said aspects and the proposed near filed assisted nanoscale patterning concepts and related configurations for achieving improved light absorption and conversion efficiency in thin film silicon solar cells.

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9180-9, Session 3

Using numerical modeling to improve the laser processing of photovoltaic devices *(Invited Paper)*

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Lasers are widely used in solar cell fabrication, to include the formation of aluminum-silicon ohmic contacts and the doping of selective emitters. The laser-materials interactions governing both of these processes are characterized by rapid heating, cooling, and solidification as well as significant alloying element vaporization and metal expulsion. However, the short time and length scales associated with these processes make it difficult for purely experimental methods to quantify the impact of these phenomena on the resulting properties and device performance. Numerical modeling techniques have been shown to be capable of providing previously unavailable insight into these complex laser-material interactions. For example, easy to use process maps of the fusion zone and heat affected zone profiles for a wide range of processing conditions can be produced to assist users in the proper selection of parameters for optimal device performance. In addition, significant insight into heat and mass transfer mechanisms and the connection between the processing conditions and device performance has been gained. A review of recent efforts in the development and application of numerical heat transfer and fluid flow models will be provided, along with the potential for future advances in the application of these models in new laser-based processing areas.

9180-10, Session 3

Large-scale atomistic simulations of the structural transformations and microstructure development in short pulse laser processing of metals *(Invited Paper)*

Leonid V. Zhigilei, Univ. of Virginia (United States)

In this project we study the ability of short pulse laser irradiation to modify the microstructure and morphology of the irradiated surface.

9180-11, Session 3

Laser processing and in situ diagnostics for crystallization: from thin films to nanostructures *(Invited Paper)*

Jae-Hyuck Yoo, Univ. of California, Berkeley (United States); Jung Bin In, Univ. of California, Berkeley (United States) and Korea Institute of Machinery & Materials (Korea, Republic of); Andy Cheng Zheng, Sang-Gil Ryu, Univ. of California, Berkeley (United States); David J. Hwang, Stony Brook Univ. (United States); Bin Xiang, Univ. of California, Berkeley (United States) and Univ. of Science and Technology of China (China); Andrew M. Minor, Costas P. Grigoropoulos, Univ. of California, Berkeley (United States)

Recent work on laser-induced crystallization of thin films and nanostructures is presented. Characterization of the morphology of the crystallized area reveals the optimum conditions for sequential lateral growth in a-Si thin films under high-pulsed laser irradiation. Silicon crystal grains of several micrometers in lateral dimensions can be obtained reproducibly. The pulsed laser crystallization is also a simple and inexpensive approach for producing circular microrings from a-Si films.

A laser beam shaping strategy is introduced to control the stochastic dewetting of ultrathin silicon film on a foreign substrate under thermal stimulation. Upon a single pulse irradiation of the shaped laser beam, the thermodynamically unstable ultrathin silicon film is dewetted from the glass substrate and transformed to a nanodome. The results suggest that the laser beam shaping strategy for the thermocapillary-induced de-wetting combined with the isotropic etching is a simple alternative for scalable manufacturing of array of nanostructures.

Laser-induced grain morphology change is observed in silicon nanopillars under a transmission electron microscopy (TEM) environment. The TEM is coupled with a near-field scanning optical microscopy (NSOM) pulsed laser processing system. This combination enables immediate scrutiny on the grain morphologies that the pulsed laser irradiation produces. The tip of the amorphous or polycrystalline silicon pillar is transformed into a single crystalline domain via melt-mediated crystallization. The microscopic observation provides a fundamental basis for laser-induced conversion of amorphous nanostructures into coarse-grained crystals.

9180-12, Session 3

Rapid sintering of copper nano ink for thin film transistor application using a laser in air environment *(Invited Paper)*

Jun Ho Yu, Jun Young Hwang, Heuiseok Kang, Kyung-Tae Kang, Korea Institute of Industrial Technology (Korea, Republic of)

Copper nanoparticles are preferred as a printable conductive material in printed electronics because they cost less than noble nano particles such as gold and silver. Only disadvantage is that copper is easily oxidized to Cu2O or CuO, which are much less electrically conductive compared than pure copper. To alleviate these problems, we propose a sintering process using a 532nm DPSS laser in the study. Copper nano ink was spin-coated on the glass substrate, and various irradiated laser powers and scan rates were applied in air environment. The resistivity of the Cu film, after DPSS laser sintering, was below 5.3 μΩcm which was about three times as much as that of pure copper

9180-13, Session 3

Sub-bandgap laser annealing of room temperature deposited polycrystalline CdTe

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The manufacturing costs of thin-film photovoltaics have steadily declined to the point where the electrically active thin-films are no longer the cost limiting factor. For instance, in CdTe solar cells the glass substrate is currently the single largest cost component. Lower cost substrates have been investigated but they typically cannot withstand very high temperatures. Therefore, current processing conditions must be modified if these substrates are to be utilized. Laser annealing (LA) further facilitates the use of these substrates by providing direct heating of the films without directly heating the substrate. We investigate room-temperature deposited CdTe and how post-deposition LA can be used to improve its structural and electronic quality. In these studies, continuous-wave, 1064nm laser light is used to anneal CdTe solar cell stacks before back contact deposition. X-ray diffraction studies show that LA reduces the concentration of structural defects associated with stacking faults. Additionally, photothermal deflection spectroscopy measurements show a reduction of sub-bandgap defects due to LA. Since the 1064nm light is only partially absorbed, in situ monitoring of the transmitted light during LA gives information on the annealing process. First principle optical modeling, combined with measured values of optical properties, allows for simulation of the observed transmission behavior. These results reveal an evolution of electronic defect annealing and surface roughness modification with laser exposure time. Two distinct LA regimes emerge: one at low power where electronic defect annealing saturates after about one minute exposure and another at high power where structural defects are annealed after several minutes exposure.

9180-14, Session 3

Laser transfer process for optoelectronic device applications

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Laser transfer process has been considered for solar cell and other optoelectronic device fabrication. It can be applied for the formation of metal contacts and achieving doping. This presentation will discuss the laser transfer process mechanism and its examples for solar cell fabrication. It is a direct write process, thus eliminating the need for photolithography. Also, this can be a low temperature process so that wafer quality is not degraded.

9180-15, Session 3

Silicon PV module customization using laser technology for new BIPV applications

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It is well known that lasers have helped to increase efficiency and to reduce production costs in the photovoltaic (PV) sector in the last two decades, appearing in most cases as the ideal tool to solve some of the critical bottlenecks of production both in thin film (TF) and crystalline silicon (c-Si) technologies. The accumulated experience in these fields has brought as a consequence the possibility of using laser technology to produce new Building Integrated Photovoltaics (BIPV) products with a high degree of customization. However, to produce efficiently these personalized products it is necessary the development of sophisticated laser processes able to transform standard products in customized items oriented to the BIPV market. In particular, the production of semitransparencies and/or freeform geometries in TF a-Si modules and standard c-Si modules is an application of great interest in this market.

In this work we present results of customization of both TF a-Si modules and standard crystalline and multicrystalline silicon modules using laser ablation and cutting processes. A comprehensive discussion about the laser processes parameterization to guarantee the functionality of the device is included. Finally some examples of final devices are presented with a full discussion of the process approach used in their fabrication.

9180-16, Session 4

Selective laser patterning in organic solar cells *(Invited Paper)*

Andreas Ostendorf, Susana Fernandes, Stella Maragkaki, Ruhr-Univ. Bochum (Germany)

Selective laser patterning for integrative serious connection has been industrially established in inorganic thinfilm solar cells based on glass substrates since a few years. In organic solar cells the used materials significantly differ in terms of their patterning behavior. also they are more susceptible to overheating. Especially challenging is the P1 process of TCO patterning on PET substrates due to the huge degree in evaporation temperatures between substrate and thinfilm. Due to their processability by wet chemical methods inverted architectures are often preferred in organic solar cells which allows the patterning by ultrashort laser pulses in substrate and superstrate configuration. Besides the pulse duration the wavelength of the laser is the most important parameter in order to avoid delamination and shoulders of the patterned rim. In our investigations we used a novel NOPA-laser system providing 20 fs pulses in the wavelength range tunable from 500-980 nm. The influence of several patterning parameters on the current-voltage-characteristics is presented.

9180-17, Session 4

Femtosecond laser processing for mobile display manufacturing

Eric P. Mottay, Clemens Hönninger, Amplitude Systèmes (France); Laurie Wilpliez, ALPhANOV (France); Jiyeon Choi, Sung-Hak Cho, Korea Institute of Machinery & Materials (Korea, Republic of); Robert Braunschweig, Amplitude Systèmes (France)

Displays are key components of many of today's mobile electronic devices such as smartphones, digital cameras, mp3 players, etc. As the market for mobile electronics expands, displays are required to fulfil more and more challenging requirements for power consumption, image quality and definition, as well as robustness.

The next generation of mobile displays offers a wider color gamut, better image contrast and lower power consumption. They also benefit from wider viewing angles, faster response and more compactness due to their thin multilayer architectures. New technologies, such as flexible displays, make extensive use of organic LEDs technology (OLED), and present significant manufacturing challenges. Production yield for such displays are currently very low; due to the complexity and the multilayer structure of the displays (up to 20 different materials). Many units come out of the production line with defects and are then discarded. The presence of dead, over-bright pixels and other imperfections are considered unacceptable in such a high added-value consumer item. As the technology extends to larger volumes and large panel displays, better production yield become critical for display manufacturers. Current laser processing technologies face limitations such as the sensitivity of organic material to heating and the low thickness of thin film layers.

Femtosecond lasers allow non-thermal ablation of materials, owing to the extremely short interaction time of the laser-matter interaction. Therefore machining precision can be significantly improved using femtosecond laser ablation as heat affected zone and debris generation is greatly reduced. In addition, non-thermal process is crucial for selective removal of multi-layer organic polymers that are susceptible to heat.

9180-18, Session 4

The effect of film properties and laser processing parameters on the laser ablation of molybdenum thin films

Eric Schneller, Rafael Rodrigues, Neelkanth G. Dhere, Univ. of Central Florida (United States); Aravinda Kar, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Molybdenum is commonly used as the electrical back contact for Cu(InGa)(SeS)2 thin-film solar cells. In order to create a monolithically interconnected device, scribing of the molybdenum layer is required. This scribe, known as the P1 scribe, is commonly carried out through laser processing. Optimization of this laser scribing has been carried out using a 532nm pulsed Nd:YAG laser. It was found that two specific regimes of processing resulted in defect free scribes. These regimes are low fluency and high pulse overlap, and high fluency and low pulse overlap. Film properties, including the microstructure, surface oxidation, and internal stress, were studied to understand their effect on the laser ablation process. It was observed that a thin layer of oxidation resulted in significant heat affected zone during the laser ablation process. A discussion of the optimal film properties and laser processing parameters is presented.

9180-19, Session 4

Laser-assisted processing of current and next generation transparent electrodes

David J. Hwang, Pyung-Cho Han, Hwan Lee, Andrew Mann, Tao Zhang, Stony Brook Univ. (United States)

Transparent conductive electrode is a critical component to realize modern optoelectronic devices including display, touchpad, and solar cells. While the most commonly used transparent electrode up to date is indium tin oxide (ITO) due to its superior optical transparency and electrical conductance, its brittleness and lithographic difficulty have posed a major challenge in manufacturing cost-effective flexible devices.

In this study, we attempt to address the aforementioned issues on the patterning of ITO film on flexible polymer substrate by direct scribing processes using short pulsed lasers. Laser parameters are rigorously tested to achieve desirable performance in terms of electrical isolation, minimal substrate damage and low degree of film delamination, considering fundamental thermo-mechanical aspects. In addition, thin coating layer of nanomaterials such as silver nanowires and carbon nanotubes is an emerging transparent electrode alternative for the next generation devices, due to its unique optical and electronic properties and low material cost. We will also report improved electrical performance by enhancing local connectivity within nanomaterials network utilizing a unique enhancement mechanism of laser field in the nanomaterials system.

9180-20, Session 4

Patterning of OPV modules by ultrafast laser

Peter Kubis, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Luca Lucera, Bayerisches Zentrum für Angewandte Energieforschung e.V. (Germany); Fei Guo, George Spyropolous, Monika M. Voigt, Christoph J. Brabec, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

In the last decade, the interest in the printable thin-film flexible organic photovoltaics (OPV) has increased enormously. Typically, photovoltaic technologies and especially OPV panels require sectioning into multiple in series interconnected cells. These interconnections can be realized with the help of 1- or 2-dimensional coating techniques but are limited in resolution. This leads to a considerable waste of the solar cell area because the interconnection area does not contribute to the photocurrent generation. However, the unique properties of ultrafast lasers are being increasingly used for material processing applications utilizing efficient, fast and localized energy deposition which leads to high ablation efficiency and accuracy in nearly all kinds of solid materials. We demonstrate a novel production process utilizing the properties of ultrafast laser ablation for OPV panels with unprecedented high module geometrical fill factor (GFF). With the combination of a precise laser beam positioning system and an ultrafast laser source operating in femtosecond regime a GFF of 97 % was reached. Further utilization of very well established slot die coating and remarkable IMI (ITO-Metal-ITO) flexible transparent electrodes allows P3HT:PCBM based large area flexible modules with high GFF and an overall efficiency exceeding 3 %. A variety of OPV module architectures like tandem and semitransparent devices are possible with the help of a sustainable and systematical procedure for the definition of ablation parameters.

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9181-1, Session 1

Nonlinear absorption and refraction spectroscopic tools *(Invited Paper)*

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We have a long history of developing techniques for the nonlinear characterization of materials. Recent work has been aimed at alleviating problems of removing background signals from solvents and substrates as well as increasing sensitivity to nonlinear refraction (NLR). In addition we are always looking for ways to increase the data rates to allow more rapid nonlinear spectroscopic measurements for absorption and refraction. Our interest is to measure both frequency degenerate and nondegenerate data.

The long-standing difficulty of measuring nonlinear refraction of solutes in low concentration solutions has been greatly reduced with the development of the Dual-Arm (DA) Z-scan techniques (ref..) which is a differential Z-scan method allowing the real-time subtraction of the solvent nonlinear refraction signal. This has increased our signal-to-noise for measuring the solute NLR by an order of magnitude.

While the Z-scan has been shown to be sensitive to NLR for optical phase distortions as small as ~10-3 waves, the EZ-scan and other variations have demonstrated sensitivities of 10x better; however, these techniques are considerably more difficult to implement. We recently introduced a new method for ultrafast NLR measurements based on the well-known photothermal beam deflection technique. We quickly found that this method was sensitive to better than 10-4 waves of phase distortion, and we are currently looking into ways to use this for rapid nonlinear dispersion measurements using white light continuum probes.

We will report on these techniques as well as some findings on various materials studied using them.

9181-2, Session 1

Thermal lensing characterization of absorption in nanodiamonds *(Invited Paper)*

Aristides Marcano, Gour S. Pati, Renu Tripathi, Yury Y. Markushin, Junwei Meng, Michael J. Williams, Delaware State Univ. (United States)

This paper reports on absorption properties of nanodiamonds of different dimensions and different concentrations of nitrogen vacancy centers. The absorption properties are measured using a photothermal lens method in the continuous wave and pulse regimes. The scattering-free character of this technique allows us to directly measure the amount of heat resulting from the absorption of electromagnetic radiation. Experiments are conducted using diode lasers at 445 nm and 670 nm for the continuous wave case, and a 1064 nm 20 ns Nd-YAG laser for the pulse regime. We use a pump-probe mode-mismatched experimental configuration where the pump beam is focused and the probe beam is collimated. We perform photothermal lens Z-scan experiments to improve the calibration of absorption and to determine the possible presence of nonlinear absorption in the sample. By comparing the results of the photothermal experiments with the conventional transmission-absorption method, we provide values for the quantum yield of scattering for the diamond nanoparticles.

9181-3, Session 1

Engineering the ground- and excited-state absorption spectra of broadband reverse saturable absorbers

Timothy M. Pritchett, Michael J. Ferry, William M. Shensky III, Andrew G. Mott, U.S. Army Research Lab. (United States); Chengkui Pei, Wenfang Sun, North Dakota State Univ. (United States)

In applications involving organic dyes exhibiting broadband reverse saturable absorption (RSA), it is frequently desirable to minimize the variation in strength of the dyes' linear absorption over the spectral range relevant to the application. At the same time, one would also like to maintain, if not increase, the strength of the dyes' excited-state absorption—which in many materials is already quite broad and relatively flat—over the same spectral range. Many square-planar platinum(II) complexes that exhibit RSA display linear absorption spectra featuring a low-energy tail that extends from the green region of the visible spectrum into the red or near-infrared and arises from singlet metal-to-ligand charge transfer (1MLCT) / ligand-to-ligand charge transfer (1LLCT) transitions. In an effort to "flatten" this absorption tail, we synthesized a series of octahedral iridium(III) complexes in which strong spin-orbit coupling induced by the iridium ion enables various singlet and triplet metal-to-ligand and ligand-to-ligand charge transfer (1,3MLCT/1,3LLCT) transitions. These give rise to a weak absorption tail between 500 and 750 nm which displays a slight "bump" in range 600-650 nm (in dichloromethane solution). The bump serves to broaden into the red the region over which single-photon absorption is sufficiently strong to populate the excited states. We discuss the design of the new chromophores, present their ground- and excited-state absorption spectra, report their photophysical parameters as determined from nanosecond and femtosecond transient difference absorption measurements and nanosecond and picosecond open-aperture Z scans, and employ these results to infer structure-property relationships for the new materials.

9181-4, Session 1

Synthesis of dual NIR two-photon absorptive [60]fullerenyl multiadducts for nonlinear light-transmittance reduction application

Seaho Jeon, Min Wang, Taizoon Canteenwala, Univ. of Massachusetts Lowell (United States); Loon-Seng Tan, Air Force Research Lab. (United States); Wei Ji, National University of Singapore (Singapore); Thomas M. Cooper, Air Force Research Lab. (United States); Long Chiang, Univ. of Massachusetts Lowell (United States)

We apply a novel molecular wrapping approach to fullerenyl hybrid triads to minimize solid aggregation in coating applications. Several C60-(antenna)x and C70-(antenna)x analogous compounds having branched hybrid triad C60(>DPAF-C18)(>CPAF-C2M) and tetrad C60(>DPAF-C18)(>CPAF-C2M)2 nanostructures, for example, were synthesized and characterized. The structural design was intended to facilitate the ultrafast fs intramolecular energy-transfer from photoexcited C60[>1(DPAF)*-C18](>CPAF-C2M)1or2 or C60(>DPAF-C18)[>1(CPAF)*-C2M]1or2 to the C60> cage moiety upon two-photon pumping at either 780 or 980 nm, respectively. The latter nanostructure showed approximately equal extinction coefficients of optical absorption over 400?550 nm that corresponds to near-IR two-photon based excitation wavelengths at 780?1100 nm for broadband nonlinear optical (NLO) applications. 2PA characteristics of these nanostructures at multiple NIR wavelengths provided support for their suitability in uses that includes

the 2PA ability of two antenna, DPAF (700?850 nm) and CPAF (850?1100 nm), and the fullerene cage at shorter wavelengths (600?700 nm).

9181-5, Session 1

Entangled two-photon absorption and virtual-state spectroscopy in diatomic molecules

Leslie Upton, Theodore G. Goodson III, Univ. of Michigan (United States)

As computational methods and experimental designs seek to utilize quantum theory to probe molecules, there is a need for more experimental and theoretical data for entangled two-photon absorption processes. With the use of nonclassical fields, we hypothesize that entangled photons can differentiate between differing absorption mechanisms of a molecule. Molecules that absorb photons via a virtual state do absorb entangled photons, while those that absorb via a permanent dipole do not. In order to explore this further, we utilize a modified entanagled two-photon absorption cross-section to compare homonuclear and heteronuclear diatomic molecules. For this study, we compare the entangled two-photon absorption cross-sections in N2 and NO.

9181-6, Session 2

Exciton fission in organic semiconductors *(Invited Paper)*

Xiaoyang Zhu, Columbia Univ. (United States)

The absorption of one photon by a semiconductor material usually creates one electron-hole pair, but this general rule breaks down in a few organic semiconductors, such as pentacene and tetracene, where one photon absorption may result in two electron-hole pairs in a process called singlet exciton. Recent measurements in our group by time-resolved two-photon photoemission (TR-2PPE) spectroscopy in crystalline pentacene and tetracene provided the first spectroscopic signatures in singlet fission of a critical intermediate known as the multiexciton state. More importantly, population of the multiexciton state is found to rise concurrently with that of the singlet state on the ultrafast time scale upon photo excitation. This observation provides an experimental foundation for a quantum coherent mechanism in which the electronic coupling creates a quantum superposition of the singlet and the multiexciton state immediately following optical excitation. We demonstrate the feasibility of harvesting the multiexciton state for multiple charge carriers or the triplets. We outline a set of design principles for molecular materials with high singlet fission yield and for the implementation of singlet fission in solar cells with power conversion efficiency beyond the Shockley-Queisser limit.

9181-7, Session 2

Ultrafast infrared spectroscopy of charge generation and transport in organic photovoltaic materials *(Invited Paper)*

John B. Asbury, Adam D. Rimshaw, The Pennsylvania State Univ. (United States)

Ultrafast infrared spectroscopy is used to examine electronic processes in organic photovoltaic (OPV) materials. We examine archetypal classes of electron acceptors in OPVs and reveal how their molecular structures determine whether hot CT state dissociation can influence the dynamics and yield of photo-generated electrons and holes. Furthermore, we tune the degree of aggregation and therefore charge carrier delocalization in OPV materials and elucidate the corresponding influence on the yield of photogenerated charge carriers in state of the art functional OPV materials and devices. The findings reveal that enhancing the degree of carrier delocalization leads to more efficient charge generation on time scales that are competitive with internal conversion to the excited state free energy surface minimum.

9181-8, Session 2

Molecular pixel system for full-color fluorescence generation *(Invited Paper)*

Soo Young Park, Seoul National Univ. (Korea, Republic of)

Current technology of color generation is based on the mixing of RGB colors emanating from different light sources and/or pixels. Unfortunately, simple mixing of RGB emitter molecules cannot provide the desired color mixing since the energy transfer between the RGB molecules are universal and unavoidable, which demands macroscopically isolated sub-pixels for the color mixed pixel. If we can find a way to completely block the energy transfer between different RGB molecules, it will make a Holy Grail for the color mixing in the molecular level. In this presentation, I will demonstrate this innovative concept of ‘molecular pixel’ which has recently been realized in my group by using functional molecules harnessing the process of excited-state intramolecular proton transfer (ESIPT).

9181-9, Session 2

Quantifying singlet fission in novel organic materials using nonlinear optics

Erik Busby, Jianlong Xia, Omer Yaffe, Bharat Kumar, Timothy Berkelbach, Columbia Univ. (United States); Qin Wu, John Miller, Brookhaven National Lab. (United States); Colin P. Nuckolls, Xiaoyang Zhu, David R. Reichman, Luis Campos, Columbia Univ. (United States); Matthew Y. Sfeir, Brookhaven National Lab. (United States)

Singlet fission is a form of multiple exciton generation in which two triplet excitons are produced from the decay of a photoexcited singlet exciton. In a small number of organic materials, most notably pentacene, this conversion process has been shown to occur with unity quantum yield on sub-ps timescales. However, a poorly understood mechanism for fission along with strict energy and geometry requirements have so far limited the observation of this process to a few classes of organic materials, with only a subset of these (most notably the polyacenes) showing both efficient fission and long-lived triplets. Here, we utilize novel organic materials to investigate how the efficiency of the fission process depends on the coupling and the energetic driving force between chromophores in both intra- and intermolecular singlet fission materials. We demonstrate how the triplet yield can be accurately quantified using a combination of traditional transient spectroscopies and recently developed excited state saturable absorption techniques. These results allow us to gain mechanistic insight into the fission process and suggest general strategies for generating new materials that can undergo efficient fission.

9181-10, Session 3

Ferroelectric liquid crystalline columns towards paintable organic ferroelectrics as characterized by nonlinear optics *(Invited Paper)*

Fumito Araoka, Daigo Miyajima, RIKEN (Japan); Takuzo Aida, The Univ. of Tokyo (Japan); Hideo Takezoe, Tokyo Institute of Technology (Japan)

Recently, we have discovered a novel ferroelectric liquid crystal (ferroelectric columnar LC: FCLC) phase in a self-organization system of polar stacks of tapered-paraffinic-wedge molecules. Its molecular design

allows hydrogen bonding among amide groups to connect the umbrella-like conical units of molecules, where the spontaneous polarization is stabilized because cyano-groups owing strong permanent dipole moment are pushed up along the columnar axis by strong binding force of the hydrogen bonding. This material system offers highly transparent and flat thin films with solution-based wet-process followed by electric field application such as corona poling, and hence may open the possibility of "paintable soft-matter nano-ferroelectrics"

Ferroelectricity in these wet-processed films was visualized with a relatively new nonlinear optical imaging technique, interferometric second-harmonic generation (SHG) microscopy, enabling the mapping of the distribution of the spontaneous polarization as well as its directional sense. Besides, detailed switching behavior of the system was discussed with SHG response together with classical electric measurements.

Stabilization mechanism of the spontaneous polarization and molecular dynamics of the ferroelectric switching have been investigated also with a nonlinear optical technique, visible-infrared sum-frequency generation (SFG) spectroscopy to probe resonant vibrational modes of molecular moieties packed in a non-centrosymmetric manner hereby contributing the ferroelectricity. These results are very important for further molecular design, particularly towards practical application.

9181-11, Session 3

Enhanced photoconductivity by melt quenching method for amorphous organic photorefractive materials

Sho Tsujimura, Kyoto Institute of Technology (Japan) and RIKEN (Japan); Takashi Fujihara, Takafumi Sassa, RIKEN (Japan); Kenji Kinashi, Wataru Sakai, Kyoto Institute of Technology (Japan); Koji Ishibashi, RIKEN (Japan); Naoto Tsutsumi, Kyoto Institute of Technology (Japan)

For many optical semiconductor field of study, high photoconductivity of amorphous organic semiconductor has strongly been desired to easily provide high device performances. This study is focused on a correlation between photoconductivity and bulk structures in amorphous organic photorefractive materials to probe the nature of the performance of photoconductivity.

The transient photocurrent experiments were carried out to evaluate the photoconductivity for two kinds of photorefractive (PR) sandwich cells fabricated through different cooling processes. PR composite films were consisted of photoconductive polymer, nonlinear optical dye, plasticizer, and sensitizer. PR composites sandwiched between two indium-tin-oxide glass plates on a hot plate were quenched or slowly cooled.

At the initial time of the transient photocurrent, the quenched sample exhibited higher photocurrent density than slowly-cooled one. This enhancement of photocurrent in quenched sample is due to an increase of carrier mobility and/or quantum efficiency. Thus, high performance of photorefractivity of quenched sample is expected. The quenched sample exhibited higher dielectric constant, which may give the proof of the difference of the bulk structures between quenched and slowly-cooled samples.

In conclusion, sample processing, in this case quenching and slowly cooling, for PR composites significantly relates to the photoconductive properties and thus PR performance of both samples will be differed. This processing method will be utilized in other amorphous organic PR materials to improve photoconductivity and photorefractivity.

9181-12, Session 3

Large optical second harmonic generation in a low-bandgap polymer

Maarten K Vanbel, KU Leuven (Belgium); Stefaan Vandendriessche, Pieter Willot, Guy Koeckelberghs, Thierry Verbiest, Katholieke Univ. Leuven (Belgium)

Recent research has focused on developing low-bandgap polymers for harvesting solar energy. Desirable properties including high power conversion efficiency, high quantum yields, high carrier mobilities and broad light absorption have been fine-tuned in these polymers. The resulting low-bandgap polymers display many advantages over classical materials, including low cost, light weight and easy processability. Research has focused on optimizing these properties, and as a result little attention has been paid to their nonlinear optical properties. For nonlinear optical applications the material must display low losses in the relevant wavelength range, as well as exhibit good thermal and temporal stability under the high incident laser powers typical of nonlinear optical experiments. We characterized the optical second harmonic generation of corona poled films of poly(cyclopenta[2,1-b;3,4-b'] dithiophen-4-ylidenedioctylmalonate). Despite the fact that this polymer is known to be amorphous, not displaying any form of order, we observed large nonlinear optical susceptibilities in these films. Coupled with the thermal and temporal stability of the polymer films, this unexpectedly large nonlinear optical response compares favorably to other novel nonlinear optical materials despite the lack of a typical donor-acceptor dye. The low absorption in the relevant wavelength region of the polymer is an additional advantage. Our results show the promise of low-bandgap polymers for nonlinear optical applications, opening an unexplored category of materials for nonlinear optical applications.

9181-13, Session 3

Dynamic amplification of light signals in photorefractive ferroelectric liquid crystals

Takeo Sasaki, Yumiko Naka, Tokyo Univ. of Science (Japan)

The photorefractive effect in photoconductive ferroelectric liquid crystals (FLCs) that contain photoconductive chiral compounds was investigated. Terthiophene compounds with chiral structure were chosen as the photoconductive chiral compounds and mixed with an achiral smectic C liquid crystal. The mixture exhibited the ferroelectric chiral smectic C phase. The photorefractivity of the mixture was investigated by two-beam coupling experiment. It was found that the FLC containing the photoconductive chiral compound exhibit a large gain coefficient of over 1200 cm-1 and a fast response time of. 900 microseconds. Optical image amplification was demonstrated. A laser beam carrying a moving image of the animation was amplified dynamically by the incident pump beam.

9181-33, Session PWed

Photo-patterning system investigating acrylate-based resin viscosity versus polymerized structure resolution

Callie I. Fiedler, Univ. of Colorado at Boulder (United States)

Three-dimensional (3D) projection stereolithography (SLA) is a common photo-patterning tool used to fabricate diverse structures ranging from biological tissue scaffolds to micro-electromechanical systems (MEMS) using a variety of polymerizeable resins. To meet the continuing expansion of SLA applications, existing approaches must be improved in material versatility, structure fidelity, and fabrication time. Resin viscosity impacts nearly all performance specifications of SLA including attainable resolution, fabrication speed and efficacy of monomer removal via solvent. To achieve maximum resolution in an SLA system, it has been hypothesized that more viscous resins lead to enhanced feature resolution by increasing monomer diffusion time. Highly viscous organic resins (> 500 cps) cannot be easily removed from systems without damaging the photopolymerized structure. We investigate the trade-off between resin viscosity and transverse feature resolution using an enclosed, single photon SLA system. The viscosity of the acrylate-based resin is modified using plasticizers and binders to reduce and increase the resin viscosity, respectively. We control axial resolution using a silane-functionalized, polymerization-inhibiting window as a substitute for the typical blade system, thus allowing for arbitrary layer thicknesses. We also demonstrate structures fabricated using a syringe-pump

deposition method that not only conserves the amount of resin required for fabrication, but also allows for simple fabrication of multi-material structures.

9181-34, Session PWed

Self-actuated origami in an optically pre-patterned two-stage photopolymer

David J. Glugla, Robert R. McLeod, Univ. of Colorado at Boulder (United States)

Origami, traditionally seen only in the context of art, has recently gained popularity as a design tool for creating complex structures from simple and compact precursors. Realization of these complex objects is achieved via a two-step process of programming an initial crease pattern into the material, followed by actuation or folding. We explore this design procedure using a two-stage photopolymer sheet created via a base mediated Thiol-Michael click reaction, whereby the material crosslink density and modulus may be spatially programmed via a series of optical exposures. Although self-actuation has been demonstrated in a variety of materials, they typically require a complex array of actuators to effect the desired fold pattern. Using the ability to modify the crosslink density and modulus of a two-stage polymer, a complex crease pattern, consisting of stiff, high modulus glassy panels and soft, flexible hinges may be prepatterned into the polymer sheet via a simple series of photopatterning steps. Self-actuation and folding may then be achieved via swelling of the low crosslink density hinges. Control over the folding direction is realized by creating a gradient in the crosslink density through the depth of the polymer sheet. In order to extend this technique, we also explore the utility of numerical optimization techniques in designing the preprogrammed crease patterns and modeling the material behavior.

9181-35, Session PWed

Design, synthesis, and optical properties of porphyrin-peptoid conjugates

Jiwon Seo, Gwangju Institute of Science and Technology (Korea, Republic of)

Porphyrins, a class of naturally occurring pigments, have been actively investigated due to their wide applications ranging from photosensitizers to new optoelectronic materials. In particular, much effort has been made to construct a defined arrangement of porphyrins. To date, most of the porphyrin displays are focused on two porphyrin π planes arranged in a side-by-side manner. In contrast, fewer face-to-face arrangement of porphyrins are reported possibly because of the lack of an efficient scaffolding material and synthetic accessibility.

Herein, we present an efficient strategy for (1) face-to-face arrangement of porphyrins, and (2) multivalent display of porphyrins on peptoid (or oligo-N-substituted glycine) helices. Distance, orientation, and numbers of porphyrins are precisely defined, which results in distinct optical and self-assembly properties of the porphyrin-peptoid conjugates. The conjugates will be useful for understanding the optoelectronic behavior of porphyrins and potentially for the development of an artificial light-harvesting system.

9181-36, Session PWed

A toy model for the nonlinear optical response of molecules with modulated conjugation

Javier Perez-Moreno, Surbhi Hablani, Quanhang Chen, Jie Li, Skidmore College (United States)

In organic molecules, the optical response originates from the motion of the pi-electrons, which are constrained to move along the molecule's conjugated path. As an electron moves through the conjugated path it interacts with the rest of the charges such as its motion is very dependent on the shape of the molecule, and specifically on the shape of the conjugated path. Previous research indicated that to improve the second order nonlinear optical response, it is best to use different kinds of spacers along the conjugated path. In this paper we introduce a simple model that allows us to evaluate how different arrangements of spacers will influence the molecule's nonlinear optical properties. Our research confirms that indeed it is best to use different kinds of spacers along the conjugated path. However, we have found that the order in which the different spacers are aligned is important. We also propose a new strategy for making more efficient molecules by combining spacers with different stabilization energy.

9181-37, Session PWed

Design and simulation of metal-insulator-metal nanoresonators for color filter applications

Saswatee Banerjee, Sumitomo Chemical Co., Ltd. (Japan)

Traditionally, liquid crystal display (LCD) systems employ color filters that are fabricated using organic dye and pigment based colorants. As a result, conventional color filters can lower the system performance by removing substantial amount of incident light through absorption. Also, the transmission bandwidth can be unacceptably large. Furthermore, there is a need to combine functions of multiple optical elements on one, facilitating miniaturization and compactness. Metal-insulator-metal (MIM) nanoresonators that can combine the functions of color filtering and polarizing can provide a useful solution to some of these issues.

An MIM nanoresonator structure is proposed for use as color filters [1]. However, the proposed structure uses high refractive index, inorganic materials in the insulator layer. Also, the bandwidth of transmission is not narrow enough to generate saturated color. Here, we simulated some MIM nanoresonator structures that might be realized using relatively low refractive index, polymeric materials and can function as polarizing, color filters in transmission mode. These structures might also yield narrower bandwidths of transmission.

The simulations are carried out using a monochromatic version of RC-FDTD [2]. This algorithm uses the 1st order Drude model [3] to evaluate the convolution operation needed to make FDTD stable for metals for which the real part of permittivity is negative. Unlike the conventional RC-FDTD [3], the Drude parameters are computed at each wavelength of the incident light using the corresponding handbook value of permittivity. Hence, this version of RC-FDTD allows us to use the handbook permittivity values at all wavelengths of operation.

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9181-39, Session PWed

Light transmission with self-assembly DNA monolayers through D-shaped optical fiber

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In recent years of DNA material research, synthesizing DNA molecular structures in an organic solvent for the mono-disperse, large area, thin-film processes has been an essential issue for optoelectronic device applications. In this study, we report a novel optical monitoring of DNA monolayers formed by a self-assembly process, where thermal history plays a key role. Discrete 2-D nanocrystal DNA structures were prepared on a side-polishing optical fiber with nanostructure patterned Au thin-film. The high evanescent field interaction between the guided light with surrounding DNA solution provided preferred directions along the 5-helix ribbon (5HR) DNA planes and double-crossover (DX) DNA planes to form DNA nanocrystals. The light guided along the fiber was received by an optical spectrum analyzer to enable spectral analyses, while morphology studies of the self-assembly DNA were performed by atomic force microscopy. We expect that this technique will provide an in-situ control of self-assembly processes for DNA and DNA-lipid complexes that will find wide applications in optoelectrical devices.

9181-40, Session PWed

Miniaturized sub-volt electro-optic modulator based on silicon integrated nanophotonics and organic polymers

Xingyu Zhang, Amir Hosseini, The Univ. of Texas at Austin (United States); Jingdong Luo, Alex K. Y. Jen, Univ. of Washington (United States); Ray T. Chen, The Univ. of Texas at Austin (United States)

Recently, silicon-organic hybrid (SOH) technology has shown to enable compact and high performance integrated electro-optic (EO) modulators. Organic EO polymer based modulators are promising for low power consumption due to the very large EO coefficient (r33) of poled polymers. Silicon photonic crystal waveguides (PCWs) infiltrated with electro-optic (EO) polymers can further reduce the device size because of slow light effects. One problem of PCW modulators is their narrow operating optical bandwidth of <1nm due to the high group velocity dispersion in the slow-light optical spectrum range. One solution is to use lattice shifting approach to provide low-dispersion slow light (constant group velocity) over a wide optical spectrum range. In this letter we report a symmetric MZI modulator based on band-engineered slot PCW refilled with EO polymer, SEO125 from Soluxra, LLC. The r33 value of poled SEO125 thin films is around 125pm/V at the wavelength of 1310 nm. The design and synthesis of SEO125 encompasses recent development of highly efficient nonlinear optical chromophores with a few key molecular and material parameters, including large ? values, good near-infrared transparency, excellent chemical- and photo-stability, and improved processability in polymers. We demonstrate a slow-light enhanced effective in-device r33 of 1190pm/V over 8nm optical spectrum range. In addition, excluding the slow-light effect, we estimate a record high in-device material r33 of 89pm/V in the slot. What is more, the utilization of large slot width provides small slot capacitance, which effectively reduces the RF power consumption to 1.5nW, which is very competitive to the state-of-the-art.

9181-41, Session PWed

Investigation of optical propagation loss in electrospun polymer nanofibers

Yuya Ishii, Shota Satozono, Ryohei Kaminose, Mitsuo Fukuda, Toyohashi Univ. of Technology (Japan)

One-dimensional nanostructures are attracting considerable attention because of unique optical interactions that arise from their subwavelength size, including light confinement, guiding, and amplification. These properties make one-dimensional nanostructures promising for applications in small optical devices such as light sources and waveguides. Electrospun polymer fibers have nanometer diameters and high aspect ratios, making them well suited for use in such optical devices. Several groups have demonstrated optical waveguiding in electrospun polymer nanofibers and evaluated propagation losses. The propagation losses are more than 10000 times higher than those of well-studied thick polymer optical fibers, although the origin of such high losses is unclear. In this work, we evaluate propagation loss in fibers at different wavelengths (?) and determine the origin of this phenomenon. We fabricate single electrospun polymer nanofibers of poly(methyl methacrylate) (PMMA) containing a small amount of Rhodamine 6G, and evaluate propagation loss at different ?. Propagation loss increased linearly with a function of ??4, and the intercept, which represents loss originating from the poor uniformity of individual fibers, is evaluated to be 6.9–22 dB cm?1 for seven single fibers. At a wavelength of 650 nm, the total propagation loss ranged from 29 to 43 dB cm?1, and the ratio of the intercept to the total loss was 19%–50%. The loss that increases as a function of ??4 is attributed to Rayleigh scattering loss resulting from density inhomogeneity of PMMA, so we concluded the high propagation loss in these fibers originates from both their poor uniformity and density inhomogeneity.

9181-42, Session PWed

Characterization of the assembly self-assembled chiral molecules in thin films by nonlinear optical microscopy and second-harmonic generation

Maarten K. Vanbel, Thierry Verbiest, Katholieke Univ. Leuven (Belgium)

Chirality at a molecular level is represented by molecules which exhibit no mirror plane in their molecular structure. In research fields such as biochemistry, biology and catalysis, chirality is one of the key parameters in the functionality of molecules. Even more in nanotechnology, chirality and chiral surfaces play an important role in the device operation and its applications. These chiral surfaces can quite conveniently be characterized by nonlinear optical techniques such as second-harmonic generation-circular dichroism. This technique is based on the difference in absorption between left and right-handed circularly polarized light, with a higher sensitivity than the linear optical variant. Integrating this technique in a microscope body enables the characterization of the chirality of inhomogeneous structures and their depth dependence. By visualizing the assembly of the chiral enantiomers in a thin film, the microscopic properties can be linked to the macroscopic alignment of the molecules.

Helical oriented molecules are an excellent test case to link intrinsic chiral properties, due to the helical direction, to the macroscopic alignment of these molecules. These helical structures were considered as chiral model structure, which interact well with different substrates, such as glass, gold or graphite.

In this work, we show the visualization of self-organized chiral molecules by means of two-photon fluorescence and second-harmonic generation. Their chirality was investigated by second-harmonic generation-circular dichroism.

9181-43, Session PWed

Improving optical limiting of cw lasers with fullerene functionalized gold nanoparticles

Maria Chiara Frare, Verena Weber, Christian Corrado De Filippo, Raffaella Signorini, Michele Maggini, Renato Bozio, Univ. degli Studi di Padova (Italy)

In recent years the increasing use of continuous wave (cw) lasers leads to the need of developing protection devices for the human eye. This kind of devices, known as optical limiters, requires smart materials that are able to reduce incoming light intensity and have fast responses and work in a wide range of wavelengths.

The limitation process exhibited by materials under cw illumination is predominantly refractive and generates a focusing or defocusing effect of the incident laser beam, usually associated with nonlinearity of thermo-optic origin. Metallic nanostructures have been studied for optical limiting devices because of their tunable optical properties.

We investigated a coupled system, consisting of dyads of gold nanoparticles (AuNPs) bound to thioled-fulleropyrrolidine (C60Py), to improve optical limiting properties of nanostructures by adding energy transfer mechanisms to the usual thermo-optic effect.

We measured the optical limiting behavior under cw illumination at 514 nm, resonant with the surface plasmon resonance at around 520 nm where the human eye is most sensitive, and thermal nonlinear optical properties, comparing results we previously obtained for AuNPs with those for AuNP-C60.

Closed aperture Z-scan measurements reveal that the non-local thermal nonlinear refraction process with a negative nonlinear index still contributes to the optical limiting action.

Time response of the material at varying input powers gives us information on the transmitted irradiance in a 300 milliseconds time interval (corresponding to the blinking time of the human eye) and shows a significant improvement of the AuNP-C60 of the AuNP alone.

9181-45, Session PWed

Strong photoluminescence characteristics of sulforhodamine B attached on photonic crystal

Kwang-Sun Kang, Kyungil Univ. (Korea, Republic of)

The optical properties of sulforhodamine B (SRH) attached on a photonic crystal by two step synthetic processes including a urethane bond formation between a 3-isocyanatopropyl triethoxysilane (ICPTES, -N=C=O) and a SRH with elevated temperature in pyridine and hydrolysis-condensation reactions between synthesized ICPTES/SRH (ICPSRH) and silica spheres. The reduction of an absorption peak at 2270 cm-1 representing asymmetric stretching vibration of –N=C=O indicates the progress of the reaction, and a new absorption peak at 1712 cm-1 characterizing –C=O stretching vibration indicates the formation of the urethane bond. The UV-visible absorption spectrum of the mixture of ICPTES and SRH show the broadened spectral line width by intermolecular interaction. The absorption peaks of SRH in methanol, ICPSRH-21h film and the silica sphere film attached the ICPSRH (ICPSRHS) are at 558, 562 and 550, respectively. The photoluminescence (PL) peak of the SRH in methanol shows a hypsochromic shift with the increase of the excitation wavelength. However, the PL peak for the ICPSRH exhibits a bathochromic shift as the excitation wavelength increases. The PL peak for the ICPSRHS shows no hypsochromic or bathochromic shift. The PL peaks for SRH in methanol, ICPSRH film and ICPSRHS film are at 568, 598 and 572 nm, respectively. The Stokes shifts of the SRH in methanol, ICPSRH-21h film, and ICPSRHS film are 10, 36 and 22 nm, respectively.

9181-14, Session 4

Nanopatterning of azo-polymers: light polarization and film thickness effects *(Invited Paper)*

Zouheir Sekkat, Moroccan Foundation for Advanced Science, Innovation and Research (Morocco)

Polymers contatining azobenzene derivatives have been the subject of intensive research for two decades owing to their unique “smartness”, i.e., the ability to tailor and/or control materials properties by photoisomerization. In particular, it was shown that photoisomerization creates optical anisotropy by nonpolar orientation, and poling by polar optical excitation (all optical poling), and it triggers molecular movement far below the glass transition temperature (Tg) of the polymer (photo-assisted poling), and polymer mass movement proceeds in spatial gradients of the excitation light (surface relief gratings). In solid polymers, photoisomerization of azobenzene derivatives creates free volume and drives efficient chromophore and polymer segmental and chain motion far below the polymer’s Tg; an effect which is at the origin of photo-assisted and all optical poling and surface relief gratings. Most of the studies reported to date on azo-polymers used single photon isomerization, and photoisomerization and photo-orientation can be achieved by by two- or multi-photon isomerization with potential applications in nanophotonics. In this presentation, I will discuss our recent work on light induced molecular movement and induced plasticity in azo-polymers by a single focused laser beam that has a longitudinal field. Nanoscale polymer movement is induced by a tightly focused laser beam in an azo-polymer film just at the diffraction limit of light. The deformation pattern which is produced by photoisomerization of the azo dye is strongly dependent on the incident laser polarization and the longitudinal focus position of the laser beam along the optical axis. The anisotropic nanofluidity of the polymer film and the optical gradient force played important roles in the light induced polymer movement. The limits of the size of the photo-induced deformation were explored, and it was found that the deformation depends on the laser intensity and the exposure time. The smallest deformation size achieved was 200 nm in full width of half maximum; a value which is nearly equal to the size of the diffraction limited laser spot. We also found that the deformation patterns induced by a longitudinal field (Ez) were strongly dependent on polymer film thickness. The polymer formed a dip at the center of the focused spot when the film thickness is thinner than 37 nm while the polymer formed a protrusion when the film thickness is thicker than 37 nm. These results imply that upward and downward forces are competing inside the polymer film and the balance between them finally decides the surface topology (dip versus protrusion) of the film.

9181-15, Session 4

Arbitrary 2D GRIN lens fabrication in diffusive photopolymers

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We introduce a new method to make gradient index (GRIN) lenses in diffusive photopolymers with nearly arbitrary two-dimensional (2D) profiles. By modulating the 2D intensity pattern and power of the exposure with a deformable mirror device (DMD), the index profile of the GRIN lens can be controlled. Combined with the self-developing nature of the photophotopolymer, rapid “on-demand” printing of arbitrary micro-optics is enabled. We demonstrate the process by fabricating Zernike polynomials and multifocal lenses.

9181-16, Session 4

Tunable non-pixelated spatial polarization shaping including an integrated optical addressing unit

Frederik Schaal, Institut für Technische Optik (Germany); Michael Rutloh, Fraunhofer-Institut für Angewandte Polymerforschung (Germany); Susanne Weidenfeld, Univ. Stuttgart (Germany); Joachim Stumpe, Fraunhofer-Institut für Angewandte Polymerforschung (Germany); Wolfgang Osten, Institut für Technische Optik (Germany)

We present a device for tunable spatial polarization shaping, based on a red light photo-addressable cell, which contains bisazobenzenes moieties and liquid crystals. The birefringence of the photo-addressable cell can be locally modulated due to the intensity of the addressing light.

The exposure with linear polarized light causes a reversible and efficient orientation of the bisazobenzene moieties, always perpendicular to the electric field of the incident light causing the alignment of the LC. This new material allows the induction of optical anisotropy generated by the irradiation with the red light. Optical anisotropy of ? /2 is reversibly and locally generated by red polarized light.

Switchable or superposable addressing patterns are generated by a micro optical addressing unit based on a VCSEL array as a linear polarized lightsource (? ~650 nm) and diffractive beam shapers for pattern generation. This enables the creation of non-pixelated spatial polarization patterns with fewer artefacts compared to devices like spatial light modulators. The induced polarization pattern is characterized by mueller matrix ellipsometry, spatial resolved rotating quarter wave plate polarimetry and polarization microscopy. Due to the compact optical addressing unit the system can be integrated into the pupil of a microscope objective, e.g. to be used for switchable phase contrast methods.

9181-17, Session 4

Morphology-dependent optical properties of polymer and small molecule materials

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In the past few years there has been increased interest in using highly ordered materials and photonic architectures to maximize the performance of organic optoelectronics. Multiple reports have demonstrated morphology-dependent electronic properties, and identified optimal device designs given strong anisotropies. The impacts, strengths, and origins of morphology-dependent optical properties, by contrast, are substantially less well understood. Here we elucidate the relationship between structure and optical properties in polymer and small-molecule materials through a suite of optical characterizations, and theoretically demonstrate an organic photovoltaic architecture which exploits optical anisotropies to drastically increase absorption in thin-films.

We study polymer (P(NDI2OD-T2)) and small-molecule (copper pthalocyanine; CuPc) films which take on different morphologies depending on processing conditions. We perform a set of optical measurements, including UV-Vis-NIR transmittance, spectroscopic ellipsometry, and photoluminescence. Using angle-resolved spectroscopies while controlling morphology, we demonstrate highly anisotropic, morphology-dependent optical properties. Understanding the connection between material structure and optical properties will be crucial for our fundamental knowledge and use of these materials in any optical device architecture. As an example, we present theoretical studies of plasmon-based light trapping, highlighting the considerable improvement possible when materials are appropriately aligned with the highly anisotropic plasmon fields. Finally, we discuss ongoing efforts to use angle-resolved spectroscopy to measure the plasmon dispersion in oriented molecular films, thus demonstrating the strong interplay between molecular orientations and device geometries.

9181-18, Session 4

Nonlinear solid-state filter based on photochromism induced by 2-photon absorption in a dye-doped sol-gel

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There is much interest in enhancement of the performance of nonlinear solid-state filters. In this work we present an advanced reversible nonlinear filter based on a dye-doped sol-gel matrix. The enhancement was achieved by using a combination of two absorption mechanisms in the same molecule; a photochromic absorption which is induced by 2-photon absorption (2PA). The 2PA serves as the trigger for initiating the photochromism through a Förster-resonance-energy-transfer (FRET) between the fluorescent donor and the photochromic acceptor. We synthesized a new bifunctional-chromophore that incorporated a Carbazole 2PA fluorescent donor and a Chromene photochromic acceptor, covalently linked together in a single molecule by a ~6 Å carboxyl group bridge. The bifunctional-chromophore was doped in an inorganic-organic hybrid matrix prepared by the fast-sol-gel process. These materials solidify without shrinkage or formation of cracks and present promising properties as optical matrices for smart filters. The dye-doped sol-gel disc presents high transparency in the visible region (“colorless”) which under UV-irradiation (one-photon absorption in the photochromic part of the molecule) transform to a strongly absorbing filter (“dark colored”), due to the conversion of the photochromic moiety to its “open” absorbing form. We have demonstrated that this ring-opening can also be induced by visible-light (620 nm) using the 2PA Carbazole-derivative portion of the molecule. We have studied fabrication routes and optical performance of these filters. We will present studies of the 2PA mechanism of the Carbazole-derivative, FRET efficiency of the combined-molecule as well as solutions of the individual moieties, and reversible dynamics of the photochromic moiety.

9181-19, Session 4

Light to work to electricity in azobenzene-functionalized linear polyimide copolymers

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Transduction of light energy into mechanical strain (photostriction) to electrical energy (piezoelectricity) has been reported. Herein, our focus is on employing materials with large displacement and high modulus to enhance photoactuation and energy transduction behaviors. Recently, we have reported on the synthesis and photomechanical response of azobenzene-functionalized polyimides. Structure-property relationships have been developed to correlate the role of crystallinity, free volume, alignment, backbone rigidity, and sub-Tg transitions to photomechanical effects observed as bending cantilevers and quantified in tensile testing. In the work presented here, we report on the synthesis and characterization of a series of azobenzene-functionalized linear polyimides. These materials were selected because of the comparatively large deflection (shape change) and elastic restoration in the dark. The displacement of these materials is further enhanced with processing (hot-drawing). The photomechanical response of these materials is large enough to stress a piezoelectric PVDF film. Subjecting the azobenzene-functionalized polyimide/PVDF system to sequenced lighting conditions (by employing a beam chopper) is shown to convert light energy, through the mechanical displacement, into electricity. The frequency of the response is shown to match the frequency of the light exposing the films.

9181-20, Session 5

Molecular magneto-optics *(Keynote Presentation)*

André P. Persoons, Katholieke Univ. Leuven (Belgium); Guy Koeckelberghs, KULeuven (Belgium); Palash Gangopadhyay, University of Arizona (United States)

A review is given on magneto-optical properties of π-conjugated polymers, in particular regioregular poly(3-alkyl)thiophenes. A theoretical formalism will be presented based upon persistent currents in organic macrocycles and cyclic structures to explain the strong Faraday rotation from thin films of these polymers. Detailed calculation on the π-electron distribution in macrocycles of poly(3-alkyl)thiophenes will be presented and related to persistent currents as previously shown to be present in mesoscopic rings of (not superconducting) metals. Synthetic aspects of these organic macrocycles, exciting new materials, will also presented at this conference. SQUID measurements on these macrocycles are undertaken to investigate the possibility of fluctuating magnetic moments in these new molecular structures. This could be the cause of giant Faraday rotation observed, as well as the ferromagnetism observed in regioregular poly(3-alkyl)thiophenes at cryogenic temperatures. Possible correlations between magnetic properties of macrocycles of π-conjugated thiophene rings and chirality of the macrocyles will be highlighted.

Experimental results on Faraday rotation studies from thin films of various polythiophene derivatives with high degree of regioregularity, but with random alkyl sidechains and of different morphologies will be presented. Possible correlations of the Faraday rotation and the supramolecular organization within these thin films will be discussed.

When appropriate, we will discuss some applications, e.g. various magneto-optic devices, or suggest directions for further research.

9181-21, Session 5

Magneto-optical properties of highly regioregular polythiophenes with different architectures *(Invited Paper)*

Nicolas Delbosc, Olivier Coulembier, Philippe Dubois, Univ. de Mons (Belgium); André P. Persoons, Katholieke Univ. Leuven (Belgium)

Since the discovery of semi-conductor properties of organic pi-conjugated systems, numerous applications of those materials have been exploited, from fundamental research to industrial commercialization. We can cite light emitting device, solar cells, electrochromic devices...

The magnetic behavior of those systems have only been studied since a short decade. Its origin lied in the existence of unpaired spins interacting together through the overlap of p-orbital creating pi-conjugation, in the chain and between the chain.

Poly-alkylthiophenes, the most studied pi-conjugated polymers in organic electronics, have been examined by Magneto-Optic polarimetry, ESR spectroscopy, SQUID magnetometry. All these measurements confirm the sensitivity of these materials to external magnetic fields , the presence of significant spin density and a different magnetic behavior dependent of the temperature .

Previous work has established some requirements to develop efficient magneto-optical materials, especially highly sensitive to very small external magnetic fields. The regioregularity of the poly-alkylthiophenes appears to be a most important parameter as well as the supramolecular organization - governed by the structure of the lateral alkyl chain - influence the magnitude of magnetization and coercivity .

Different architectures of polythiophene have been synthesized, statistical copolymer of thiophene to obtain very low semi-crystalline character polythiophene, and highly regioregular macrocyclic polythiophene to probe the existence of persistent currents.

9181-22, Session 5

Chiral Supramolecular Assemblies from Achiral and Chiral Molecules Investigated by Second Harmonic Generation at the Air-Water Interface

(Invited Paper)

Aurélie Bruyère, Univ. de Claude Bernard Lyon 1 (France); Laure Guy, ENS Lyon (France); Amina Bensalah-Ledoux, Stephan Guy, Univ de Claude Bernard Lyon I (France); Emmanuel Benichou, Pierre-François Brevet, Univ. Claude Bernard Lyon 1 (France)

We show, using Second Harmonic Generation (SHG) at the air-water interface, that chiral supramolecular assemblies can be formed under lateral compression from a monolayer of achiral molecules. The polarization analysis of the nonlinear optical intensity provides further insights into the origin of the response. We demonstrate that for two different amphiphilic compounds, namely 4-(4-(dihexadecylamino)styryl)-N-methylpyridinium iodide (DiA) and 5-(octadecyloxy)-2-(2-thiazolylazo) phenol (TARC18), the SHG response is of magnetic dipole nature and we present a nonlinear correlation method to monitor these supramolecular assemblies at the air-water interface.

9181-23, Session 6

All-organic plasmonics *(Invited Paper)*

Mikhail A. Noginov, Guohua Zhu, Lei Gu, John K. Kitur, Norfolk State Univ. (United States); Viktor A. Podolskiy, Univ. of Massachusetts Lowell (United States); Evgenii E. Narimanov, Purdue Univ. (United States); Jarrett Vella Jr., Augustine M. Urbas, Air Force Research Lab. (United States)

Metallic response in the optical range (supporting localized or propagating surface plasmons), optical gain (compensating surface plasmon loss and providing for stimulated emission), and nonlinearity (enabling tuning) are the necessary ingredients of active plasmonics, whose applications range from sensing to future nanocircuitry operating at optical frequencies.

We show that all three critical functions can be realized in dye-doped polymers. Thus, population inversion and optical gain can be easily created in many laser dyes, negative (real) dielectric permittivity can be obtained in the vicinity of strong absorption bands, and index of refraction of dye-doped particles can be controlled by Q-switched laser pumping.

9181-24, Session 6

Optical properties of Alq3 films and Alq3/plasmonic heterostructures *(Invited Paper)*

Hans-Peter Wagner, Niranjala D. Wickremasinghe, Masoud Kaveh, Milhan Ajward, Xiaosheng Wang, Univ. of Cincinnati (United States); Heidrun Schmitzer, Xavier Univ. (United States); Qiang Gao, Chennupati Jagadish, The Australian National Univ. (Australia)

Tris (8-hydroxyquinoline) aluminum (Alq3) is a frequently used emissive material in organic light emitting devices. However, the contribution from interacting molecules to the photoemission is still rather unexplored. To gain more insight into such processes we investigate the radiation of optically excited excitons by intensity dependent time-integrated (TI) as well as time-resolved (TR) photoluminescence (PL) measurements at temperatures ranging from 15 to 300 K. The Alq3 films were grown by organic molecular beam deposition (OMBD) on Si substrates. At low temperature (15 K) we find a significant reduction of the light emission which is attributed to bimolecular quenching of singlet excitons which are captured in extended traps. At higher temperatures (150 K) the quenching effect is remarkably reduced due to thermally activated occupation of non-quenchable exciton states.

Alq3 is also an excellent organic component to fabricate plasmonic heterostructures. We investigate the mode properties of OMBD grown Alq3 waveguides comprising one or more thin metal layers using the m-line technique. The investigations show that strategically placed metal films can be used to selectively excite plasmonic and dielectric TM modes and to shift and suppress TE modes. We further explore the exciton dynamics in polytype wurzite/zincblende InP nanowires which are coated with few 10 nm thick Alq3 and Mg:Ag metal layers using TI and TR optical methods. The Alq3 spacer between nanowire and metal layer is used to passivate the nanowire surface and to control the energy-transfer from nanowire excitons to plasmon oscillations in the deposited metal film.

9181-25, Session 6

Plasmonic mode amplification using organic semiconductor gain media *(Invited Paper)*

Deirdre M. O'Carroll, Sarah Goodman, Jesse Kohl, Rutgers, The State Univ. of New Jersey (United States)

Coupling of gain materials to metallic nanostructures and thin films offers an avenue for amplification of plasmonic modes in both confined and extended geometries. In the past decade, a deeply sub-wavelength analogue to the laser, using surface plasmons instead of photons has been proposed and demonstrated. Additionally, propagating surface plasmon polaritons (SPPs) on extended metallic films have been amplified using gain media to achieve chip-scale propagation lengths. Here, we investigate amplification of resonant and propagating surface plasmon modes using organic polymer semiconductor gain media. These gain media are of interest because: (1) unlike laser dye molecules, they do not undergo significant concentration quenching in the solid-state and, therefore, can result in a high chromophore density in the optical near-field of the metal structure; (2) the oscillator strength and transition dipole orientation of the polymer gain medium can be manipulated offering selective coupling or excitation of particular plasmonic modes.

For resonant surface plasmon amplification, we fabricate gold nanorod-conjugated polymer core-shell nanoparticles through a miniemulsion synthesis process. A more distinct threshold in emitted intensity as a function of optical pump energy is observed from these hybrid structures compared to polymer nanoparticles and dissolved polymer molecules. This is attributed, in part, to the higher quality factor of the hybrid nanoparticle. Demonstrations of amplified SPP modes supported by conjugated polymer/metal/insulator asymmetric planar waveguides will also be reported. Theoretical work predicts increased SPP mode leakage by factors of up to 88 when the polymer undergoes stimulated emission. Gain measurements on fabricated structures support these findings.

9181-26, Session 6

Enabling enhanced emission and low threshold lasing of organic molecules using special Fano resonances of macroscopic photonic crystals

Bo Zhen, Song-Liang Chua, Jeongwon Lee, Massachusetts Institute of Technology (United States); Alejandro W. Rodriguez, Princeton Univ. (United States); Xiangdong Liang, Steven G. Johnson, John D. Joannopoulos, Marin Soljacic, Ofer Shapira, Massachusetts Institute of Technology (United States)

The nature of light interaction with matter can be dramatically altered in optical cavities, often inducing nonclassical behavior. In solid-state systems, excitons need to be spatially incorporated within nanostructured cavities to achieve such behavior. Although fascinating phenomena have been observed with inorganic nanostructures, the incorporation of organic molecules into the typically inorganic cavity is more challenging. Here,we present a unique optofluidic platform comprising organic molecules in solution suspended on a photonic crystal surface, which supports macroscopic Fano resonances and allows strong and tunable interactions with the molecules anywhere along the surface. We develop a theoretical framework of this system and present a rigorous comparison with experimental measurements, showing dramatic spectral and angular enhancement of emission. We then demonstrate that these enhancement mechanisms enable lasing of only a 100-nm thin layer of diluted solution of organic molecules with substantially reduced threshold intensity, which has important implications for organic light-emitting devices and molecular sensing.

9181-32, Session 6

Nonlinear optical photovoltaics

Jean-Michel Nunzi, Somayeh M. A. Mirzaee, Queen's Univ. (Canada)

Nonlinear absorption was investigated in a poly (3-hexylthiophene) (P3HT) PCBM fullerene blend, one of the most popular organic solar cell's materials. We observed three-photon absorption in the bulk hetero junction photodiode configuration. The output photocurrent of the photodiode was interpreted in terms of the three-photon absorption properties of the P3HT:PCBM blend at 1550 nm.

Can the concept be extrapolated to high efficiency solar cells?

We propose an optical antenna technology revisited with plasmonics and organic rectifiers that should permit the development of an ultra-high efficiency PV technology that is compatible with large-area fabrication (self assembling) and low-cost (plastic) technologies.

9181-28, Session 7

New frontier of organic electro-optic (EO) materials and devices: from molecular engineering to technology innovations *(Invited Paper)*

Alex K. Y. Jen, Univ. of Washington (United States)

For E-O materials to be useful for device applications, the material development should proceed in parallel with innovative device concepts and device fabrication process. Recently, the unique properties of organic NLO materials have also inspired the development of novel nanofabrication methods to replace more traditional techniques and has potential to lead to scalable nanophotonics based on organic NLO materials. Moreover, implementation of a clever designed device structures and fabrication process not only can significantly improve device performance but also reduce energy consumption during operation.

Recent development of highly efficient organic EO materials and devices has opened the way to promising opportunities to complement and improve current inorganic semiconductor based technologies. For example, organic EO materials can provide a full array of optical functions and can be processed at temperatures that are compatible with CMOS integrated circuits. In respond to exponentially increasing demands for operational bandwidth, structured organic EO materials are expected to play critical role in organic silicon hybrid nanophotonics in the near future. The ability to efficiently guide and control an optical signal in field confined nanoscale integrated devices will significantly boost the performance for structured organic EO materials. Integrated optical circuits based on organic silicon hybrid EO materials will enable low cost, mass production of novel nanophotonic devices for broadband optical signal processing and communications.

9181-29, Session 7

Design and fabrication strategies for high transparency polymer nanocomposites with dynamic tunable optical response *(Invited Paper)*

Michael R. Bockstaller, Alei Dang, Krzysztof Matyjaszewski, Chin Ming Hui, Carnegie Mellon Univ. (United States)

Recent progress in the molecular engineering of organic-inorganic hybrid materials facilitates the fabrication of hybrid materials with unprecedented control of the composite microstructure from the nano- to the micrometer lengthscale. This contribution will discuss strategies to harness the increased level of microstructural control to modulate the interaction of inorganic fillers with light and to facilitate dynamic property changes induced by light-filler interaction. Two examples from recent research in our group will be presented to illustrate how the strategic design or placement of inorganic fillers can be applied to control the electric field distribution such as to enhance or reduce absorption and scattering processes in microstructured hybrid materials. In the first example, the strategic arrangement of inorganic (metallic) elements in a polymeric matrix will be shown to facilitate optical resonant tunneling effects that give rise to tunable passbands in metallodielectric polymer composites. The second example will discuss opportunities to control light-filler interactions by means of tailoring the ligand-chemistry of particle fillers. A novel synthetic technique to precisely control the composition of polymeric ligands will be introduced and applied to the synthesis of high transparency composite materials with inorganic content in excess of 50% by volume. Augmenting the polymeric component with two-photon absorbing functionality will be shown to impart power-flux sensitivity to light-filler interactions that can be harnessed, for example, for the fabrication of dynamically responsive optical elements.

9181-30, Session 7

Small bending loss of thiacyanine polariton nanofibers

Hiroyuki Takeda, National Institute for Materials Science (Japan); Kazuaki Sakoda, National Institute for Materials Science (Japan) and Univ. of Tsukuba (Japan)

In this presentation, we give a firm theoretical proof of extremely small bending loss of thiacyanine nanofibers, which was recently found by Takazawa's experimental study (Takazawa et al., Phys. Rev. Lett. 105, 067401 (2010)).

For this purpose, we first analyzed the exciton-polariton dispersion relation of the thiacyanine nanofiber characterized by its highly anisotropic polaritonic refractive index. We formulated a plane-wave expansion method by which we could obtain the eigenfrequencies of polaritons as eigenvalues of a non-Hermitian and frequency-independent matrix (Takeda & Sakoda, Phys. Rev. B 86, 205319 (2012)). The group refractive index calculated from the slope of the dispersion curve agreed quite well with the Fabry-Perot interference patterns found in both the calculated and observed transmission spectra. We found that the dispersion relation of the anisotropic polariton was quite different from the isotropic case and depended strongly on the tilt angle of the optical transition dipole moment of the constituent molecules to the fiber axis.

Secondly, we theoretically examined the bending loss. We formulated a finite-difference frequency-domain method stabilized by a conformal transformation to calculate the bending loss as a function of the radius of curvature and the propagation frequency (Takeda & Sakoda, Opt. Express 21, 31420 (2013)). Our numerical results supported Takazawa's experimental observation. The present study clearly shows that the polariton nanofiber gives a novel possibility for bent waveguides to fabricate optical microcircuits and interconnection that cannot be attained by the conventional waveguides based on the index guiding.

9181-31, Session 7

Detuning of polar whispering gallery modes in polystyrene microspheres

Heidrun Schmitzer, Xavier Univ. (United States); Julie Lutti, Paola Borri, Wolfgang Langbein, Cardiff Univ. (United Kingdom); Hans-Peter Wagner, Univ. of Cincinnati (United States)

Optical whispering gallery modes (WGMs) in microcavity optical resonators are promising as pressure or force sensors for microfluidic flow applications. It is the high Q-factor of the WGMs which makes microcavity resonators extremely sensitive to changes in their shape or in their refractive index. Any of these changes will be detectable as a frequency shift of the resonating modes. If the resonating microsphere is subjected to mechanical stress, the induced frequency shift is directly related to the exerted force.

In this work, we investigate the detuning of polar WGMs in solid polystyrene microspheres (PMs) which are mounted between windows of a flow chamber as a function of axisymmetric stress. The stress on the PMs is varied by applying uniaxial stress on one window using a calibrated cantilever and by hydrostatically pressurizing the flow chamber liquid with a syringe creating a counteracting force on the side walls. The applied uniaxial stress reduces the geometrical circumference of the PM and increases locally the refractive index at the flattened poles. We observe that the polar WGMs shift to higher frequencies with increasing pressure and that the magnitude of this strain-induced shift depends on the mode order. Furthermore, an energy splitting between azimuthal modes occurs which is linearly increasing with pressure. A theoretical model based on a classical ray optics approach is presented which reproduces the main results of our experimental observations.

9182-1, Session 1

Large range reflection notch tuning in polymer stabilized cholesteric liquid crystals *(Keynote Presentation)*

Timothy J. White, Air Force Research Lab. (United States); Kyung Min Lee, Air Force Research Lab. (United States) and Azimuth Corp. (United States); Vincent P. Tondiglia, Air Force Research Lab. (United States) and SAIC (United States); Timothy J. Bunning, Air Force Research Lab. (United States)

We report on large range reflection notch tuning in polymer stabilized cholesteric liquid crystals. Tuning is observed in formulations based on negative dielectric anisotropy liquid crystals by stabilization with 3-10 wt% polymer in the presence of applied DC fields. The underlying mechanism is ionic charge trapping. The talk will survey improvements in tuning range, threshold voltage, and optical properties through monomer formulation, holographic photopolymerization, and the inclusion of additives.

9182-2, Session 1

Vertical-cavity surface-emitting laser with liquid crystal external cavity

Yi Xie, Jeroen Beeckman, Univ. Gent (Belgium); Krassimir Panajotov, Vrije Univ. Brussel (Belgium); Kristiaan Neyts, Univ. Gent (Belgium)

We have developed a technology to integrate a thin layer of liquid crystal (LC) on top of a Vertical Cavity Surface Emitting Laser (VCSEL). The VCSEL and the LC layer can be electrically driven independently. The LC layer can modulate the refractive index and therefore the polarization state of the VCSEL. Based on this technology, VCSEL devices with tuneable external cavity are achieved by using nematic LC incorporated with an additional reflector or chiral liquid crystal (CLC).

Firstly, an external cavity for the VCSEL is provided by a dielectric mirror (SiO_2/Ta_2O_5) and a thin layer of LC between it and the VCSEL. The reflection band position is designed for the emission wavelength of the VCSEL by choosing the right thickness of the periodic bi-layers. By changing the voltage across the LC layer, the optical length in the external cavity can be tuned. Therefore, the emitting properties of the LC-VCSEL, including polarization state, emission wavelength and threshold current, can be controlled by the voltage applied on the LC layer.

Secondly, the external cavity is formed by a layer of CLC. The concentration of the chiral dopant is chosen such that the CLC has a reflection band for one circular polarization for VCSEL emission wavelength. The CLC properties are temperature dependant so that the emission properties of the CLC-VCSEL can be controlled by device temperature. Compared with the stand-alone VCSEL, the CLC-VCSEL has a smaller threshold current, a larger wavelength tuning range and a purely circular polarization with a higher degree of polarization.

9182-3, Session 1

Light-induced effects in dye-doped liquid crystals: role of space charges *(Invited Paper)*

Francesco Simoni, Liana Lucchetti, Univ. Politecnica delle Marche (Italy)

The main motivations of the investigation performed on light-induced effects in dye-doped liquid crystals are: (i) the research of a suitable photo-alignment technique to be used in display technology and in optical memory devices; (ii) the discovery of the huge nonlinear response of mixtures doped by Methyl-Red making possible applications in the field of optical processing with extremely low power.

From the results of these investigations in nematics doped by Methyl-Red a basic question arises: is there a link between the transient reorientation leading to the extraordinarily large nonlinear response observed at low light intensity and the permanent photo-alignment observed at higher light doses?

We report here the simple demonstration that both effects have the same origin being dependent on the modification of the space charge density induced by light at the irradiated surface. This result is achieved by recording the effect of irradiation of this type of samples by applying an external voltage and comparing the results obtained under dc and ac conditions. In fact while the dc field favors the formation of a space charge at the sample surfaces, an ac field prevent its formation. With dc field our data show the occurrence of all the reorientation processes. On the contrary, when an ac field is applied, only photo-isomerization occurs being effective only in the high dose regime.

9182-4, Session 1

Laser effect within an optical spatial soliton in nematic liquid crystals *(Invited Paper)*

Jean-François Henninot, Univ. d'Artois (France); Mardia Ouali, Univ des Sciences et Technologies de Lille (France); Jean-François Blach, Univ. d'Artois (France); Majid Taki, Univ. des Sciences et Technologies de Lille (France)

The spatial solitons have been studied for two decades in nematic liquid crystals (NLC). The outstanding properties of these materials in terms of index modulation due to a high birefringence allowed a series of experimental studies in order to verify theoretical models. The results presented here follow the observation of the phenomenon of self-focusing as it has been observed in NLC doped with dyes [1]. It was shown that the index variation in the origin of the focusing process associated to a high non-locality stabilizes the solitons in a (2D+1) configuration. It is now worth the trouble for going further in the process to observe the behavior of such solitons in active medium and to study the conditions for obtaining gain in such a system. The addition of a dye to the NLC generates fluorescence. By inserting such a soliton in a cavity it is possible to study the mechanism for obtaining gain at relatively low power, the losses being limited by the lateral guide corresponding to the soliton. The presentation will be organized as follow: A first step has involved the study of processes of radiative and non-radiative losses of the soliton obtained by continuous pump. The second part is associated with the behavior of the soliton inserted in a resonant cavity. This part aims to define the optimal conditions for obtaining longitudinal cavity modes of a soliton confined between two mirrors. The search for stability conditions of the cavity will then be discussed.

9182-5, Session 1

Synthesis, liquid-crystalline behavior, and photoluminescence properties of novel Au(I) complex with naphthalene ring in a mesogenic core *(Invited Paper)*

Yuki Rokusha, Ritsumeikan Univ (Japan); Nana Sugimoto, Ritsumeikan Univ. (Japan); Shigeyuki Yamada, Ritsumeikan Univ (Japan); Osamu Tsutsumi, Ritsumeikan Univ. (Japan)

Gold(I) complexes show strong luminescence via intra- or intermolecular Au(I) Au(I) interaction (aurophilic interaction). Therefore, their quantum yields of photoluminescence are enhanced in the condensed phases, in where the molecules are packed closer than in solutions, and one can expect that the gold complexes are possible candidate materials for fabricating light-emitting devices. It has been reported that luminescent

properties of these complexes depend on the aggregation structure in the condensed phases; thus, the aggregation structure of the complexes should be controlled to make them suitable for luminescence. In order to control the aggregation structure of the gold complexes, we have designed and synthesized liquid-crystalline (LC) gold(I) complexes with disc-like or rod-like molecular shape. Disk-like LC molecules can be organized spontaneously into columnar structures, known as the discotic columnar phase. Because the molecules are stacked closely in the columnar phases, we considered that the columnar aggregation structure should be suitable for luminescence. The synthesized disk-like LC complexes showed no photoluminescence in dilute solutions. Luminescence was enhanced in the condensed phases: strong photoluminescence (? > 40 %) was observed at room temperature in the crystalline phase. We found that purple-yellow-red tricolor luminescence was obtained from a single material and the luminescent color can be controlled by thermal phase transition. In the rod-like LC complexes, intense photoluminescence (? > 50 %) was also observed. Very interestingly, when the rod-like gold complexes were introduced in side-chains of polymers as a mesogen of polymer LCs, white-color photoluminescence was observed from a single material.

9182-6, Session 2

Light-emitting liquid-crystal displays constructed from AIE luminogens *(Keynote Presentation)*

Dongyu Zhao, Hong Kong Univ. of Science and Technology (Hong Kong, China) and School of Chemistry and Environment Science, Beijing University of Aeronautics and Astronautics (China); Anjun Qin, South China Univ. of Technology (China); Ben Zhong Tang, Hong Kong Univ. of Science and Technology (Hong Kong, China) and South China Univ. of Technology (China); Wai Tung Leung, Hong Kong Univ. of Science and Technology (Hong Kong, China)

Liquid crystal displays (LCDs) are widely used in many aspects of our life from handheld personal devices to flat-panel televisions. Since LCDs are passive display devices, they usually have narrow viewing angles and low brightness. Light-emitting LCDs (LELCDs) are envisioned as less energy consuming display devices. To realize LELCDs, fluorescent materials with strong solid-state emissions are required. Many luminophores, however, suffer from heavy aggregation-caused quenching effect in the solid state. In order to overcome the shortcoming, we synthesized a liquid-crystalline luminogen TPE-PPE consisting of a tetraphenylethylene core and four mesogenic peripherals. TPE-PPE shows aggregate-induced emission (AIE) and thermotropic liquid crystallinity. By doping a tiny amount of TPE-PPE into a nematic LC host PA0182, linearly polarized emission was obtained on the unidirectional orientated LC cell. The photoluminescence polarization ratio of the LC cell reached to 4.16 in the directions perpendicular and parallel to the rubbing direction. Through utilizing the emission anisotropy of TPE-PPE, two kinds of LELCD devices were successfully fabricated. This approach simplifies device design, lowers energy consumption, and increases brightness of LCD. The LELCD may find technology applications in the area of anti-counterfeiting.

9182-7, Session 2

Fast algorithms for liquid crystal modelling *(Invited Paper)*

Thomas P Bennett, University of Southampton (United Kingdom); Yogesh Murugesan, Univ. of Southampton (United Kingdom); Keith R Daly, University of Southampton (United Kingdom); Giovanni De Matteis, Northumbria University (United Kingdom); Giampaolo D'Alessandro, Univ. of Southampton (United Kingdom)

The geometry of modern liquid crystal devices can be quite removed from the idealised case of a planar liquid crystal cell: the device boundary may be structured in a way that induces bistability; the liquid crystal may contain suspensions of particles that enhance or modify its linear or nonlinear behaviour; there may be nanostructured surfaces or scaffolding immersed in the liquid crystal to produce tunable metamaterials.

Modelling these devices requires accurate and efficient computational tools to determine the director alignment. In this talk I will illustrate examples of how mathematical analysis of the liquid crystal dynamics equations can lead to approximate models that have a very large range of applicability and that can be solved numerically at a fraction of the cost of the original liquid crystal equations.

For example, it is well known that the Q-tensor equations for liquid crystal alignment are numerically stiff, i.e. they contain two very different time scales. The first relates to the collapse of the scalar order parameter to the nematic state, while the second describes the alignment of the liquid crystal under the influence of the boundaries and of external fields. Using the method of multiple scales it is possible to separate the two time scales and obtain approximate equations for the Q-tensor reorientation dynamics. Comparison with numerical simulations of the full equations show that the error in the approximation is smaller that one part in ten thousand, while the computational speed is increased a hundredfold.

9182-8, Session 2

Molecular dynamics in azobenzene liquid crystal polymer films studied by transient grating technique *(Invited Paper)*

Kenji Katayama, Shota Kuahara, Tomoki Ikeda, Chuo Univ. (Japan)

Transient grating (TG) technique is one of the time-resolved spectroscopic technique, which provides much information on the dynamics of photochemical or photophysical processes via a refractive index change in a time-resolved manner. We have developed a new type of transient grating, called heterodyne transient grating (HD-TG) method, featuring highly sensitive detection due to heterodyne detection, simple optical setup, and applicability for various sample conditions such as rough surface, heterogeneity, etc.[This method has been applied to liquid crystal (LC), and photopolymer, recently and the molecular dynamics was studied in a wide temporal range, from the nanosecond to second order.

Here, we studied the photo-induced molecular motion in a LC polymer film including azobenzene. The film was confined in a liquid crystal cell, while it is a photomobile film under a free standing condition, which is triggered by the photoisomerization of azobenezene. By observation of the refractive index change induced by a pulse laser, contraction of the film was observed on the order of several hundreds of nanoseconds, and the subsequent reorientation and molecular rotation dynamics was observed from a few microseconds to a hundred milliseconds. Finally, the cis isomer of azobenzene was thermally returned back to the trans isomer about a few seconds because the film could not be bent in the liquid crystal cell. Since the contraction, reorientation and molecular rotation took place before the cis to trans transformation, these processes correspond to the preliminary molecular motion preceding the macroscopic bending of the film.

9182-9, Session 2

Mechanoresponsive change in photoluminescent color of rod-like liquid-crystalline compounds and control of molecular orientation on photoaligned layer *(Invited Paper)*

Mizuho Kondo, Kentaro Okumoto, Seiya Miura, Mayuko Hashimoto, Ryohei Fukae, Nobuhiro Kawatsuki, Univ. of Hyogo (Japan)

Mechanochromic luminescence (MCL) is referred to the phenomenon whereby an isothermal change in photoluminescence in excess of two states, and at least one pathway is induced by mechanical stimuli such as grinding, shearing, pressing and stretching. This property is expected for mechanical sensor, cellular imaging, detection of microenvironmental changes, and optical memory. Various types of MCL compounds have been reported and recently, Kato and co-workers reported series of liquid-crystalline MCL compounds, which demonstrates mechanically induced change in photoluminescence by tuning molecularly assembled structures. On the other hand, we focused on liquid-crystalline MCL compounds on alignment layer. We have previously prepared two types of asymmetric oligothiophenes containing cyano- and pyridyl- molecular terminals and control their molecular orientation by using photoalignment layer. These molecules contain electronically push-pull structure and easy to be introduced in rodlike MCL compounds. Additionally, controlling the molecular alignment of MCL compounds with photoalignment layer have potential to succeed in functional MCL film such as polarized micropatterned MCL and directional detection of mechanical stimuli. Herein, we prepared asymmetric rodlike MCL compounds containing cyano- and pyridyl molecular terminal and explored their photoluminescence behavior under mechanical stimulus. Upon grinding, both powder of the cyano- and pyridyl-terminated compounds change its photoluminescent color and reverted to its initial color by heating above its melting point. The cyano-terminated MCL was aligned along the orientation direction of photoalignment layer and pyridyl-terminated MCL exhibited uniaxial alignment when it coated on photoaligned film containing carboxylic acid.

9182-36, Session 2

Large aperture and polarizer-free liquid crystal lenses for ophthalmic applications

Yi-Hsin Lin, Hung-Shan Chen, Yu-Jen Wang, Chia-Ming Chang, National Chiao Tung Univ. (Taiwan)

A large aperture and polarizer-free liquid crystal lens (LC lens) for ophthalmic application is demonstrated. The LC lens with electrically-controlled positive lens and negative lens power can not only provide for the correction of myopia but also for the correction of presbyopia. In 2013, we proposed a LC lens with 6mm aperture size and with the tunable lens power from -1.2 D ~ +2D. However, the aperture size is still small comparing to the existing ophthalmic lenses and tunable lens power is small. To overcome the hinder of the lenses power, multi-layered structure must be adopted. In this paper, we propose a polarizer free LC lens with 4 LC layers separated by three liquid crystal and polymer composite films (LCPCFs). The functions of LCPCF are as separators and alignment layers. A high resistive layer is also adopted to lower the voltage. The operating principles for adopted a LC lens in human eye system are introduced. The lens power for the aperture size of 10mm is -2.2D ~ +3.3D (5.5D in total). The lensing effects are shown and discussed. We believe this study provides a guideline to help the researchers and engineers to develop the large aperture LC lens for ophthalmic lens applications.

9182-11, Session 3

Imaging and visualization of complex nematic fields *(Keynote Presentation)*

Slobodan ?umer, Univ. of Ljubljana (Slovenia) and Jo?ef Stefan Institute (Slovenia); Miha ?an?ula, Univ. of Ljubljana (Slovenia); Simon ?opar, Univ. of Ljubljana (Slovenia) and Jo?ef Stefan Institute (Slovenia); Miha Ravnik, Univ. of Ljubljana (Slovenia)

Geometrical constrains and intrinsic chirality in nematic mesophases enable formation of stable and metastable defect structures of high complexity. Recently knots and links of arbitrary complexity have been formed using laser micro-manipulation of nematic braids entangling colloidal particles in nematic liquid crystals [Tkalec et al., Science 2011]. In frustrated chiral nematic phases stable and metastable toron and hopfion defects have been implemented by laser tweezers [Smalyukh et al., Nature Materials 2010; Chen et al., PRL2013]. In numerical studies we predicted numerous exotic structures in confined blue phases [Fukuda & Zumer, Nature Comms 2011 and PRL 2011] and stable knotted disclinations in cholesteric droplets with homeotropic boundary conditions [Sec et al., Nature Comms 2014]. Modelling studies based on the numerical minimisation of the phenomenological free energy, supported with the adapted topological theory [Copar & Zumer, PRL 2011] allow predicting all of the listed nematic defect structures. Crucial for the understanding of the structures is the visualisation of the nematic ordering. It will be illustrated how the director, order parameter, and their derivatives can be used to point out particular aspects of ordering [Copar et al., Liquid Crystals 2013]. Finally the numerically obtained structures will be used to simulate polarisation microscope images and in more detail the images that can be obtained with three-photon excitation fluorescence polarizing microscopy for selected types of polarization [Trivedi et al., Optics Express 2010].

9182-12, Session 3

Liquid crystal hyperbolic metamaterial for wide-angle negative-positive refraction and reflection *(Invited Paper)*

Grzegorz Pawlik, Wroclaw Univ. of Technology (Poland); Wiktor Walasik, Aix-Marseille Univ. (France); Karol Tarnowski, Antoni C. Mitus, Wroclaw Univ. of Technology (Poland); Iam-Choon Khoo, The Pennsylvania State Univ. (United States)

We show that nanosphere dispersed liquid crystal (NDLC) metamaterial can be characterized in near IR spectral region as an indefinite medium whose real parts of effective ordinary and extraordinary permittivities are opposite in signs. Based on this fact we design a novel electrooptic effect: external electric field driven switch between normal refraction, negative refraction and reflection of TM incident electromagnetic wave from the boundary vacuum/NDLC. A detailed analysis of its functionality is given based on effective medium theory combined with a study of negative refraction in anisotropic metamaterials, and Finite Elements simulations. Preliminary results of full-wave simulations are presented.

9182-13, Session 3

Optical vortex modulated by liquid crystal Q-plate fabricated via photo-alignment *(Invited Paper)*

Andy Y. G. Fuh, Yao-Han Huang, Ming-Shian Li, National Cheng Kung Univ. (Taiwan)

The electro-optical characterics of liquid crystal (LC) devices, q-plate (QP) and advanced LC q-plate (ALCQP) fabricated using axially symmetric photo-alignment are investigated. The experimrntal results show that the electrically tunable LC QP device could be modulated to control the shape and polarization of a linearly polarized Gaussian laser propagating through the sample, while an ALCQP device could be modulated to control the shape of a circularly polarized Gaussian laser beam. Notably, a Gaussian beam modulated by LC q-plate and ALCQP under suitable applied voltages can be changed to various beam shapes with helical wave-fronts, as demonstrated by Michelson's interference. Details of sample fabrications and experimental results are reported.

9182-14, Session 3

Tunable refractive index in an optically isotropic liquid crystal phase *(Invited Paper)*

Mamatha Nagaraj, The Univ. of Manchester (United Kingdom);

Verena Gortz, Lancaster Univ. (United Kingdom); John W. Goodby, The Univ. of York (United Kingdom); Helen F. Gleeson, The Univ. of Manchester (United Kingdom)

We present an electrically tunable refractive index observed in an isotropic liquid crystal phase, exhibited by a bent-core liquid crystal, known as the dark conglomerate (DC) phase. This unusual change in the refractive index has not been reported before in the DC phase of other bent-core liquid crystals. It occurs because of a series of electric-field-driven transformations that take place in the DC phase of the studied bent-core liquid crystal. These transformations give rise to a decrease in the refractive index of the system, when an electric field is applied across the device, and no change in the birefringence is seen during such behavior.

The electro-optic phenomenon corresponding to an unusual change in the refractive index without changing the birefringence of an optically isotropic phase could be exploited for number applications, where the applied electric field, by modulating the refractive index of the liquid crystal, changes the nature of the propagating light wave. These mainly include integrated optical modulators such as optical waveguides and for fiber-optic core, liquid crystal phase gratings and liquid crystal based tunable lenses.

The electro-optic phenomenon will be presented and the possibility of exploiting this for a number of liquid crystal based device applications will be discussed.

9182-15, Session 3

Harnessing optical vortex lattices in nematic liquid crystals *(Invited Paper)*

Marcel G. Clerc, Univ. de Chile (Chile); Stefania Residori, Umberto Bortolozzo, Institut Non Linéaire de Nice Sophia Antipolis (France); Raouf Barboza, Estefania Vidal, Univ. de Chile (Chile); Gaetano Assanto, University Roma Tre, (Italy)

By creating self-induced vortexlike defects in the nematic liquid crystal layer of a light valve, we demonstrate the realization of programable lattices of optical vortices with arbitrary distribution in space. On each lattice site, every matter vortex acts as a photonic spin-to-orbital momentum coupler and an array of circularly polarized input beams is converted into an output array of vortex beams with topological charges consistent with the matter lattice. The vortex arrangements are explained on the basis of light- induced matter defects of both signs and consistent topological rules.

9182-16, Session 4

Ultrahigh sensitivity in liquid-crystal-based immunodetection by surface modification of the alignment layer *(Invited Paper)*

Mon-Juan Lee, Chang Jung Christian Univ. (Taiwan); Hui-Wen Su, Shih-Hung Sun, Wei Lee, National Chiao Tung Univ. (Taiwan)

It is known that liquid crystals (LCs), with thermotropically calamitic nematics such as 5CB in particular, can be employed in biological sensing and applied to label-free immunodetection owing to their unique birefringent, anchoring, alignment and collective properties. Like all different kinds of immunoassays, both sensitivity and specificity are universally the most important key points of concern. For such a relevant LC-based immunodetection technique to be promising, it must be able to yield good performance as manifested by the resulting sensitivity and specificity. In order to warrant desired high sensitivity, various methods can be simultaneously adopted in the sample fabrication procedure.

In this invited talk, I shall report on our recent development of various approaches toward ultrahigh sensitivity in LC-based immunoassays for potential clinical applications. The approaches entail (1) the selection of the sensing mesogen; (2) an unconventional method for antibody–antigen reaction; (3) the surface modification of the surfactant layer for LC alignment. The measurements involve polarizing optical microscopy as well as the contact-angle measurement. Special attention will be paid to the conspicuousness of the optical texture varying with the cancer biomarker CA125 antibody/antigen concentration and to the extent of surface modification of the aligning layer on the substrate as revealed by the contact-angle data.

9182-17, Session 4

Contact angle measurements as a means of probing the surface alignment characteristics of liquid crystal materials on photoalignment layers *(Invited Paper)*

Kenneth L. Marshall, Oleg Didovets, Debra J. Saulnier, Univ. of Rochester (United States)

Photoalignment technology has been under increasingly intensive investigation over the past decade as an alternative to buffing for generating high-quality uniform molecular alignment in liquid crystal (LC) devices. This technology is especially applicable to LC devices for high-peak-power laser applications, as the 1054 nm laser damage thresholds of photoalignment layers can approach that of fused silica (over 60 J/cm2, 1 ns pulse). The high laser damage resistance of coumarin-based photoalignment layers enabled us to fabricate a wide variety of photoaligned LC devices for high peak power laser applications, including wave plates, beam shapers, apodizers, and radial polarization converters. Although considerable progress has been made in this area, materials selection and photoalignment processing conditions are still determined using a largely empirical, “trial-and-error” approach, which is a costly and time-consuming process. Because the contact angle of an LC droplet with an alignment surface yields important information about LC-surface physical interactions (e.g. surface polarity, wettability and LC surface tension), and these interactions can be correlated to important device parameters of interest (fast axis direction, pretilt angle, and anchoring energy) contact angle characterization has the potential to be a useful, convenient, and cost-effective metric to aid in material selection and process development for photoaligned LC device fabrication. In this paper, we will describe efforts to correlate the contact angle of LC materials with a wide range of physical properties with alignment quality in several photoalignment materials systems, and demonstrate how the technique could be used to optimize photoalignment exposure processes.

9182-18, Session 4

Nanoparticles forming liquid crystals *(Invited Paper)*

Ewa Gorecka, Univ. of Warsaw (Poland)

Research related to nanoparticles (NPs) is stimulated by their unusual optical, electronic and magnetic properties. The range of application could be broader if they form well defined, large-scale structures; such supercrystals are referred to as artificial solids. We show that spherical nanoparticles can organize into many diverse structures when substituted by mesogenic ligands, due to the selfsegragation of chemically non-compatible units. Nematic, smectic columnar and 3D superstructures were observed in which metal cores and organic parts self-segregate in space. The type of structure can be controlled by composition of grafting layer and temperature as well as by the metal core size and density of grafting layer. In special cases the distance between nanoparticles in the superlatice could be controlled by light induced conformational changes in organic grafting layer. In some cases birefringent supercrystals were observed that gave possibility to control the plasmonic properties by the light polarization. When the fluorescent ligands are attached to the metal surface the enhancement of fluorescence form the ligand was detected if ligands were alligned parallel to the NP surface. The mesogenic ligands can be also used for controlling of metal core growth (Ostwald effect).

9182-19, Session 4

Investigation of host liquid crystal composition on polymer stabilised blue phase properties *(Invited Paper)*

Suhana B. Mohd Said, Md Asiqur Rahman, Univ. of Malaya (Malaysia); Itaru Yamana, Munehiro Kimura, Nagaoka University of Technology (Japan)

Polymer stabilised blue phase liquid crystals (PSBPLCs) have been investigated for photonics and display applications for the following reasons: optical isotropy in the dark state, ease of fabrication due to the omission of the alignment layer, and sub-millisecond response length. Major barriers to the commercialisation of PSBPLCs are: hysteresis, residual birefringence, and most significantly, high driving voltage. We have chosen to lower the driving voltage through optimization of the mixture (host LC, chiral dopant and monomer). In this paper, investigation of the contribution of the host liquid crystal to the phase stability and electro-optic characteristics of the PSBP will be discussed. The following cases have been investigated:

1. A three component host liquid crystal (E8, PE-5CNF (4-Cyano-3-fluorophenyl 4-pentyl benzoate) and CPP-3FF (4-(trans-4-n-propyl cyclohexyl)-3',4'-difluoro-1,1'-biphenyl), LCC Corporation, Japan). For a ratio of E8:PE-CNF:CPP-3FF of 5:3:2, a large BPI window of >50.4 degrees C and low hysteresis was achieved, but the driving voltage was 79V.

2. A single host liquid crystal, 8OCB with chiral dopant CB15. For a ratio for 8OCB:CB15 of 1:1, this mixture demonstrated a significantly lower driving voltage of 65V, but exhibited a smaller BPI window of >27 degrees C. Decrease in the ratio of 8OCB:CB15 also induced the presence of a BPII phase in the mixture. A single host liquid crystal has the advantage of simplicity of composition, and lowered driving voltage. However, the hysteresis and blue phase temperature range needs to be optimised.

This investigation concludes upon the suggestion of liquid crystal characteristics which optimises the blue phase temperature range, low hysteresis, switching times and driving voltage.

9182-21, Session 4

How the physical anisotropy affects the bacteria movement *(Invited Paper)*

Tigran V. Galstian, Ismaël Duchesne, Simon Rainville, Univ. Laval (Canada)

Liquid crystals have been successfully used in light modulation applications. Their "sensing" capacities were less explored, particularly in the area of medical diagnostics. Given the numerous presence of liquid crystalline structures in the biological tissue, we have raised the question of the impact of the physical anisotropy of a liquid environment on the behavior of living microorganisms, such as bacteria. We have discovered that this may drastically change the behavior of bacteria. The corresponding studies may teach us how the human body is colonized by those bacteria. In this talk, we shall present various liquid crystalline media as host for living microorganisms and the study of the behavior of one example of them (E-coly bacteria) in a biocompatible liquid crystal composition.

9182-22, Session 5

Liquid crystal polymer dispersed liquid crystals *(Keynote Presentation)*

Nelson V. Tabiryan, Olena Uskova, Luciano De Sio, Uladzimir Hrozhyk, Rafael O. Vergara-Toloza, BEAM Engineering for Advanced Measurements Co. (United States); Timothy J. White, Timothy J. Bunning, Air Force Research Lab. (United States)

A Liquid Crystal polymer is used for realizing a new generation of Polymer-Dispersed Liquid Crystals (LCPDLC) with excellent optical/electro-optical properties and negligible scattering losses in both ON and OFF states. The polarized optical microscopy and the environmental scanning electronic microscopy show a regular and uniform morphology made of well oriented polymeric stripes without the evidence of micro-sized nematic liquid crystals droplets. Moreover, we have characterized the LCPDLC structures in terms of spectral analysis response, operating voltages and switching times. In comparison to conventional polymer liquid crystal composite systems, our LCPDLC structures exhibit low switching voltage (4-5V/µm), submillisecond (400?s) and symmetric response times. The stability of the alignment has been tested by applying a quite large electric field (8-9V/µm) as well as by performing temperature cycles across the nematic-isotropic phase transition point (80 °C). In both cases, the goodness of the LCPDLC alignment proved to be not affected by the tests. In addition, due to the robustness of the polymeric structure, the LCPDLC film can be easily removed (without affecting the optical quality) from the glass substrates and used in a free-standing configuration. The possibility to realize a stable and well oriented liquid crystal film with all the properties above described marks a breakthrough towards the realization of solid high speed photonic devices.

9182-23, Session 5

Liquid crystal phases and charge carrier mobilities for a series of monoalkoxy-ethyloxycarbonyl derivatives of the tetracyclic oligothiophene BTTT

Michael T. Springer, Rebecca A. Callahan, Renfan Shao, Yongqiang Shen, Univ. of Colorado at Boulder (United States); Garry Rumbles, National Renewable Energy Lab. (United States); Noel A. Clark, David M. Walba, Univ. of Colorado at Boulder (United States)

Organic photovoltaic devices suffer from inefficiencies resulting from non-uniform molecular alignment in thin films; controlling thin film morphology is a top priority for OPV. Liquid crystals can provide this control by utilizing the well-defined self-assembly of mesogens. Crystal phases (SmBcrystal, SmE, SmG, SmH) that lie below hexatic smectic phases (SmB, SmF, SmI) are particularly well aligned and in particular, the SmE phase shows relatively high charge carrier mobilities in, e.g., OFET devices. The SmE phase shows long-range order in three dimensions and it has recently been postulated that this order results from the interdigitation of alkyl chains between smectic layers. A similar result has been found for the polymer poly(2,5-bis(3-tetradecylthiophen-2-yl) thieno[3,2-b]thiophene) (pBTTT), where interdigitation of alkyl chains yields a highly ordered morphology. pBTTT has shown charge mobility values among the highest of any organic material, 1 cm2 V-1 s-1, and Hanna has recently reported carrier mobilities greater than 5 cm2 V-1 s-1 for a benzothienobenzothiophene derivative processed from a smectic liquid crystal phase. Here we report on an efficient synthesis of 2-alkoxy-BTTT analogs, and on the morphology and charge carrier mobilities in several smectic and plastic crystal phases observed in the system, including SmB, SmE, and SmG. Mobility and absorption data have also been acquired on spin-coated thin films of the materials.

9182-24, Session 5

Electrooptics of nematics formed by molecular dimers *(Invited Paper)*

Oleg D. Lavrentovich, Jie Xiang, Sergij V. Shiyanovskii, Kent State Univ. (United States); Corrie Omrie, Univ. of Aberdeen (United Kingdom); Volodymyr Borshch, Young-Ki Kim, Afsoon Jamali, Kent State Univ. (United States); Georg H. Mehl, Maria-Gabriela Tamba, The Univ. of Hull (United Kingdom)

Electrically induced reorientation of liquid crystal (LC) director caused by dielectric anisotropy is a fundamental phenomenon widely used in modern technologies. We report on the experimental observation of electrooptic effects in nematic liquid crystals formed by dimer molecules with flexible bridge connecting two rigid rod-like units. The materials exhibit three nematic phases: nematic, chiral nematic (when doped with chiral additives) and twist-bend nematic. The uniaxial nematic shows a regular Frederiks type of response while the twist bend nematic shows the first order Frederiks transition, in which the type of deformation is reduced to splay and saddle splay of the helicoidal axis by the periodic nature of director modulation. The electrooptic behavior is thus similar to dielectric reorientation of smectic A and short-pitch cholesterics. The chiral nematic demonstrates an electrooptic effect with a distinct heliconical deformation of the director. In the electric field, the director forms an oblique helicoid. The pitch and the conical angle of the oblique helicoid are both dependent on the applied electric field. The work is supported by NSF DMR grants 1121288 and 1104850, by DOE Grant No. DE-FG02-06ER 46331, Ohio Research Scholars Program Research Cluster on Surfaces in Advanced Materials and by KSU Trustees Fund.

9182-25, Session 5

New twist on the helical nanofilament phase of bent-core liquid crystals *(Invited Paper)*

Antal I. Jakli, Cuiyu Zhang, Oleg D. Lavrentovich, Kent State Univ. (United States)

The B4 phase of bent-core liquid crystals has been shown to be an assembly of twisted layers stacked to form helical nanofilaments. Interestingly, some of them have structural colors that cannot be explained by the nanofilaments alone. Cryogenic-transmission electron microscopy observations on 40-120 nm films of four bent-core liquid crystal materials show that the filaments are present even in contact with a carbon substrate with only minor deformation, thus representing bulk properties. We find that the subsequent arrays of nanofilaments are not parallel to each other, but rotate by an angle of 35-40 degrees with respect to each other. This doubly twisted structure can explain the structural color. Being principally different from the packing of molecules in the twist grain boundary and blue phases, the double-twist structure of helical nanofilaments expands the rich word of nanostructured organic materials.

9182-26, Session 5

Tailored liquid crystal devices for specific imaging applications *(Invited Paper)*

Avner Safrani, Iftach Klapp, Asi Solodar, Marwan Abuleil, Sivan Isaacs, Ibrahim Abdulhalim, Miri Gelbaor Kirzhner, Ben-Gurion Univ. of the Negev (Israel)

The emerging field of liquid crystals (LCs) photonics is becoming more and more active research field in which the strong electrooptic properties of LCs are harnessed for these applications such as the use of LC spatial light modulators (SLMs) in imaging, tunable focus LC lenses, tunable filters and polarization control devices in optical telecommunication and imaging. LCs can flow and fill small gaps; hence they can be integrated into nanophotonic structures in planar or cylindrical geometries such as in photonic crystal fibers.

Our group has been developing variety of specially designed LC devices integrated into imaging systems for specific applications such as (i) wideband tunable filters for hyperspectral imaging and frequency domain optical coherence tomography, (ii) discrete tunable filter for multispectral imaging, (iii) compact polarization rotator for polarimetric imaging, (iv) fast phase retarder for phase shift interferometry, (v) wideband achromatic waveplate, (vi) annular SLM for extended depth of focus, (vii) polarization independent LCFP tunable filter, and lately (vii) optically addressed SLMs. The main concepts of these devices and their functionality into imaging systems such as in skin spectropolarimetric imaging and full field optical coherence tomography will be reviewed in this talk.[1-5]

Selected Publications:

1. Avner Safrani and I. Abdulhalim, Optics Letters, 34, 1801-3 (2009).

2. O. Aharon and I. Abdulhalim, Optics Express, 17, 11426-33 (2009).

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4. Avner Safrani and I. Abdulhalim, Optics Letter 37, 458 (2012).

5. Iftach Klapp, Asi Solodar, I. Abdulhalim, Tunable extended depth of field using a liquid crystal annular spatial filter, accepted to Optics Letters, 2014.

9182-27, Session 5

Infrared reflector based on liquid crystal polymers and its impact on thermal comfort conditions in buildings

Hitesh Khandelwal, Technische Univ. Eindhoven (Netherlands) and Dutch Polymer Institute (Netherlands); Franziska Roberz, Roel C. G. M. Loonen, Jan L. M. Hensen, Cees W. M. Bastiaansen, Dick J. Broer, Michael G. Debije, Albert P. H. J. Schenning, Technische Univ. Eindhoven (Netherlands)

An energy crisis is one of the most challenging problems throughout the world. There has been a huge increase in global demand of energy in last few years. Several attempts have been made to decrease the consumption of energy sources. One of the main energy consumption in building, cars, greenhouses and indoor spaces is by cooling devices to maintain the indoor temperature in comfortable zone. To reduce the consumption of tremendous amount of energy on cooling devices we need an improved control of transparent features (i.e. windows) for reduction of energy.1 Therefore, IR-Reflector is interesting for the rejection of infrared light and this device would be very attractive especially if working mechanism of IR Reflector does not affect light in the visible region without using any source of energy.

A very appealing method to selectively and precisely control infrared transmission is via the use of cholesteric liquid crystal polymer reflectors (Ch-LC polymer). Ch-LCs, also known as chiral-nematic LCs; reflect circularly polarized light as a result of their self-organizing molecular helices.2 Depending on the handedness of the pitch, left- or right-handed circularly polarized light is reflected. The pitch of the helix in these networks determines the wavelength of reflection, and can be modified in response to light3 and temperature4 resulting in a change in reflection wavelength. In contrast to existing alternatives they are characterized by a very sharp cut-off between the transmissive and the reflective state enable exact tailoring of the heat reflection. In my presentation, I will be discussing the fabrication of hyper-reflective infrared broadband and its implications on the temperature of buildings.

Acknowledgement

This research forms part of the research programme of the Dutch Polymer Institute (DPI), project #764.

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(2) Heynderickx, I.; Broer, D. J. Molecular Crystals and Liquid Crystals 1991, 203, 113.

(3) White, T. J.; Bricker, R. L.; Natarajan, L. V.; Tabiryan, N. V.; Green, L.; Li, Q.; Bunning, T. J. Advanced Functional Materials 2009, 19, 3484.

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9182-28, Session 6

Micro-second electro-optic modulation in polymer/liquid-crystal nanocomposite films *(Keynote Presentation)*

Masanori Ozaki, Osaka Univ. (Japan); Yo Inoue, Kyoto Univ. (Japan); Hoe-Kyeong Kim, Hiroyuki Yoshida, Osaka Univ. (Japan)

We report a high-speed electro-optic modulation of the refractive index (RI) of a polymer/liquid-crystal composite film possessing a rise time < 30 microseconds and a decay time < 10 microseconds. The fast response was demonstrated in a polymerized LC film containing nano-sized LC droplets less than 20 nm inside a sponge-like anisotropic polymer matrix. The film was fabricated simply by irradiating ultraviolet light on a mixture comprising photo-polymerizable and conventional LCs. For the photo-polymerized LC matrix, a variety of films with various distribution of optical anisotropy can be used such as nematic, cholesteric and so on. In any case, only the effective RI can be tuned without disturbing a distribution of the molecular orientation in the polymerized LC matrix. For instance, in the composite film using the photopolymerized cholesteric LC as the matrix, a selective reflection can be controlled by modulating the effective RI without deforming the helical structure. Because of nano-sized droplets dispersed in the matrix, there is no light scattering and fast relaxation dynamics of the confined LC molecules enable a micro-second modulation of the selective reflection. Using dye-doped cholesteric matrix, micro-second tuning of lasing wavelength can also be achieved. The lasing color tuning previously reported in the chiral LCs has been based on the pitch-tuning, namely deformation of the helix, and the tuning response of the lasing is quite slow. Adapting the composite system proposed here, fast and continuous color modulation based on the RI-tuning can be performed.

9182-29, Session 6

Ultrafast all-optical switching with transparent liquid crystals

Shuo Zhao, Iam Choon Khoo, The Pennsylvania State Univ. (United States)

We present the results of our recent studies of ultrafast all-optical switching using laser induced refractive index change in transparent liquid crystals. The underlying mechanism involved is nematic flow induced director axis reorientation caused by Maxwell Stress imparted by the laser. This process is characterized by response times in the nanoseconds time scale. The feasibility of all-optical switching using such mechanism has been experimentally demonstrated along with quantitative theoretical modeling which gives very good agreement with the experimental results. In particular, we showed that the response times become shorter with increasing input laser power, with the shortest switching time around 20 nanoseconds – about 1 million times faster than the conventional electro-optical switching counterpart. Since the effect is non-resonant, it could be observed with laser of any wavelength in the entire visible – near IR region, and utilized for passive optical limiting and sensor protection application against agile frequency lasers.

9182-30, Session 6

Liquid crystal tunable THz wave plates *(Invited Paper)*

Yan-Qing Lu, Wei Hu, Nanjing Univ. (China)

We developed a serial of large birefringence (> 0.3) nematic liquid crystal (LC) mixtures in the wavelength range from 0.5 to 2 THz. Based on the obtained materials, some THz devices have been developed. Among them, a tunable THz wave plate is demonstrated. We use a metallic grating as front polarizer and electrode. A tree-layer graphene film is used as a transparent and polarization independent back electrode. Photoalignment technique is adopted to obtain a homogeneous LC alignment. If an electric field is applied, the phase retardation of the LC cell changes so that output THz beam is electrically controlled. For a 2 THz wave, the polarization state evolution in 0-50V voltage range is recorded, which clearly show the change from a linear polarization, to elliptical polarization, circular polarization then back to an orthogonal linear polarization. The function of a tunable THz half-wave plate (HWP) is well-displayed.

In comparison with previous reported LC THz phase shifters, our tunable wave plate shows some interesting advantages, (1) High birefringence LC mixture is used. (2) The polarization rotation and EO tuning are demonstrated with only 50 V driving voltage. (3) Unique cell structure containing a built-in metallic grating polarizer/electrode and a lost-cost three layer graphene electrode. (4) A post treatment technique is developed to greatly improve the transmission of graphene in THz band. (5) Photo alignment technique is employed. We believe our technologies may pave a road toward many new LC tunable THz apparatuses.

9182-31, Session 6

Liquid crystal claddings for passive temperature stabilization of silicon photonics

Joanna N. Ptasinski, Space and Naval Warfare Systems Ctr. Pacific (United States) and Univ. of California, San Diego (United States); Iam-Choon Khoo, The Pennsylvania State Univ. (United States); Yeshaiahu Fainman, Univ. of California, San Diego (United States)

Silicon photonics allows for high density component integration on a single chip and it brings promise for low-loss, high-bandwidth data processing in modern computing systems. As optics penetrates deeper into the chip, temperature stability becomes essential due to silicon's high thermo-optic coefficient, consequently leading to performance deterioration in the presence of rising temperature. This work explores passive thermal stabilization of silicon photonic devices using nematic liquid crystal (NLC) claddings. Liquid crystals possess large negative thermo-optic coefficients in addition to low absorption at the telecommunication wavelengths.

9182-32, Session 6

Glass-free 3D display with LCD: technique challenges, approaching solutions, and prospect *(Invited Paper)*

Jianying Zhou, Sun Yat-Sen Univ. (China)

Technical challenges for autostereoscopy, or glass-free 3D display system are presented. These challenges include the reduction of the cross talk between different viewing channels, the increase of the resolution for each viewing point as well as technological and cost competitiveness with flat 2D display systems. The approach with a back-light illuminated LCD system, including the design of multi-viewing points, the hybrid spatial and temporal control, the use of a new figure of merit to guide the optical systematic design with a genetic algorithm to achieve a smallest possible cross talk and a viewing zone with homogeneous intensity, is presented. We show that it is possible to achieve the display quality approaching a glass-assisted 3D system, and the integrated user-machine interaction is developed demonstrating the possibility that autostereoscopic display may experience a fresh development for the reason that it may become a rigid demand for the end users in the near future.

9182-33, Session 7

Lasing and waveguiding in smectic A liquid crystal optical fibers *(Keynote Presentation)*

Igor Musevic, Jo?ef Stefan Institute (Slovenia); Karthik Peddireddy, Max Planck Institute for Dynamics and Self-Organization (Germany); Venkata S. R. Jampani, Jo?ef Stefan Institute (Slovenia); Stephan Herminghaus, Christian Bahr, Max Planck Institute for Dynamics and Self-Organization (Germany); Marusa Vitek, Jo?ef Stefan Institute (Slovenia)

We demonstrate a new class of soft matter optical fibers, which are self-assembled in a form of smectic-A liquid crystal microtubes grown in an aqueous surfactant dispersion of a smectic-A liquid crystal. The diameter of the fibers is highly uniform and the fibers are highly birefringent. They are characterized by a line topological defect in the core of the fiber with an optical axis pointing from the defect core towards the surface. We demonstrate guiding of light along the fiber and Whispering Gallery Mode (WGM) lasing in a plane perpendicular to the fiber. The light guiding as well as the lasing threshold are significantly dependent on the polarization of the excitation beam. The observed threshold for WGM lasing is very low when the pump beam polarization is perpendicular to the direction of the laser dye alignment and is similar to the lasing threshold in nematic droplets. The smectic-A fibers are soft and flexible and can be manipulated with laser tweezers demonstrating a promising approach for realization of soft photonic circuits

9182-34, Session 7

Real-time holographic display using doped liquid crystals *(Invited Paper)*

Yikai Su, Shanghai Jiao Tong Univ. (China)

We discuss dynamic optical holographic displays based on liquid crystals doped with dye and quantum dot, respectively. Real-time holographic display is achieved with a response time of ~1ms in a dye-doped liquid crystal film without any applied electric field. Meanwhile, the reconstructed RGB images are combined into a color image. The dependences of the response time and diffraction efficiency on the polarizations of the control beams are investigated. We also demonstrate a quantum-dot-doped liquid crystal to improve the diffraction efficiency. The transient first-order diffraction efficiency is measured up to 20%. A reconstructed holographic video at a refresh rate of 25 Hz is demonstrated by the experiments.

9182-35, Session 7

Cholesteric liquid crystals with wide-band reflection properties *(Invited Paper)*

Huai Yang, Lanying Zhang, Peking Univ. (China)

Attributing to the unique helical supra-molecular structure, cholesteric liquid crystal (CLC) performs selective light reflection property and could reflect the circularly polarized incident light whose handedness is identical with the helical axis. But the bandwidth of a single-pitch CLC is usually less than a hundred nanometers, which is insufficient for its some applications. Recently in our group, a transparent polymeric film with ultra-broad wavelength reflection of infrared (IR) was prepared. Three polymerizable liquid crystal (LC) photo-polymerizable monomers: nematic monoacrylated, nematic diacrylated and smectic monoacrylated monomers were synthesized. The mixture of these monomers could organize themselves with smectic-like short-range ordering (SLSO) between the Ch and smectic A (SmA) phase. After mixing UV-absorbing dye and photo-initiator with the monomers of which the molecules of the Ch phase were oriented planarly, the mixture was cured under UV irradiation at the temperature just above the SLSO region. Since an UV-intensity gradient resulted from the dye, polymerization-rate gradient were achieved, and the more nematic diacrylated diffused to the region nearer the UV light in the film. Thus, the temperature region of the SLSO increased during UV irradiation and the resulted film had a very large pitch gradient which can reflect the circularly polarized incident light from 700 to 14000 nm.

9182-37, Session 7

Color sequential TFT-LCD toward an eco display, from perspective of liquid crystal and TFT driving *(Invited Paper)*

Han-Ping D. Shieh, National Chiao Tung Univ. (Taiwan)

High efficiency, low material cost, green are among key features for eco-displays. In this talk, the suppression of the serious color break-up (CBU) artifact and improvement of image quality, the human visual model for CBU, LC display without polarizing optics, novel image driving algorithm and TFT driving for an Eco Display will be presented. Novel TFT material, backlight and system toward 3D and interactive will be explored.

9182-40, Session 7

New developments in SmAPF materials

Eva D. Korblova, Maria Kolber, Joseph E. Maclennan, Matthew A. Glaser, Renfan Shao, Yongqiang Shen, Noel A. Clark, David M. Walba, Univ. of Colorado at Boulder (United States)

The first reported SmAPF phase, obtained from the mesogen W586, exhibited interesting and useful electrooptics.(1) Specifically, upon application of an electric field, a significant increase in birefringence is observed without rotation of apparent optic axis. Further study demonstrates great promise for this phase in applications requiring fast phase-only electrooptic modulation.

In order to tune properties of SmAPF materials for such applications, a search for new mesogens providing wider phase temperature ranges and improved modulation depth (birefringence change with field) alone or in mixtures, is in progress.

Several surprising and interesting discoveries have derived from this work. For example, a dramatic and unexpected odd-even effect in homologues of W586, which possesses a tricarbosilane-terminated alkoxy tail, provides insights into the nature of nanophase segregation in smectics.

In addition, new classes of SmAPF mesogens have been prepared in an effort to produce materials for applications. Details of the characterization and EO properties of the new materials will be presented.

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9182-38, Session 8

The helical nanofilament phase for organic photovoltaics *(Keynote Presentation)*

Rebecca A. Callahan, Michael T. Springer, Eva D. Korblova, Renfan Shao, Univ. of Colorado at Boulder (United States); David Coffey, Garry Rumbles, National Renewable Energy Lab. (United States); Noel A. Clark, David M. Walba, Univ. of Colorado at Boulder (United States)

The helical nanofilament (HNF) liquid crystal phase represents a unique hierarchical assembly of bent-core mesogens.[1] In the bulk

HNF phase, smectic stacks possess spontaneous negative Gaussian curvature, limiting the width of the layers (~ 40nm, and the number of layers in a stack (~40 nm), providing long helical nanofilaments ~ 40 nm diameter, which then self-organize into a porous hexagonal array of HNFs. Furthermore, half the surface area of the HNFs is composed of layer edges, putting the aromatic sublayers in direct contact with the surroundings, which can contain any one of many nanophase segregated dopants up to concentrations ~ 50% by weight. These dopants can be soluble fullerenes such as PCBM, in which case the doped sample represents an ordered bulk hetereojunction (BHJ) system with possible application in organic photovoltaics (OPV). This gains added attractiveness due to the additional hypothesis, supported by solid state NMR data, that the aromatic core sublayers in the HNF phase are effectively crystalline in nature. Recent studies using flash photolysis time-resolved microwave conductivity suggesting efficient exciton splitting from excited PCBM in a prototypical HNF mesogen/PCBM BHJ, and reasonable hole carrier mobilities in the HNF phase, will be described.

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9182-39, Session 8

Photoinduced deformation of uncrosslinked liquid crystal polymers *(Invited Paper)*

Yanlei Yu, Jiu-an Lv, Yuyun Liu, Fudan Univ. (China)

Photodeformable crosslinked liquid-crystalline polymers (CLCPs) are most promising materials for applications such as artificial muscles and soft actuators. Since on the one hand, they are able to show large and reversible shape deformation due to the cooperation of the rubber elasticity of polymer networks and high order of liquid-crystalline (LC) mesogens. On the other hand, they can convert light energy directly into mechanical work and act by remote, instant, and precise manipulation. In this work, novel azobenzene-containing side-chain liquid crystal polymers without any crosslinking were synthesized via ring opening metathesis polymerization (ROMP), which are benefit for the fabrication of micro and even nano soft actuators through micromachining technologies. We designed the such uncrosslinked LC polymers (UCLCPs) based on the following four factors: (1) ROMP that allows for controlled living polymerization was employed to synthesize the UCLCPs with a high molecular weight, thus they are easy to self-assemble into freestanding films without any chemical crosslinking; (2) azobenzene groups in the side chains create the photoresponsiveness and act as mesogens to form an LC phase; (3) mainchain of the UCLCPs has a rubbery-like structure, which endows the UCLCPs with a good elasticity; (4) flexible mainchains, sidechains with long spacers and end-groups enable the polymer excellent processability. Upon one-step annealing, the UCLCPs with azobenzene mesogenic side chains self-assembled into freestanding films, where the polymer backbone aligned parallel to the film surface and the side chains aligned atilt away from the surface. Such an ordered structure forms through the self-assembly of a smectic C phase. The resultant wide-area ordering configuration allows the polymer films to bend away from the light source rapidly and reversibly when the azobenzene units are photoisomerized.

9182-41, Session 8

Physics of scattering texture of novel siloxane based smectic A liquid crystal materials *(Invited Paper)*

Mykhaylo N. Pivnenko, Daping Chu, Univ. of Cambridge (United Kingdom)

No Abstract Available

9182-42, Session 8

Photo-aligned ferroelectric liquid crystals for modern photonics *(Invited Paper)*

Abhishek K. Srivastava, Vladimir G. Chigrinov, Hoi Sing Kwok, Hong Kong Univ. of Science and Technology (Hong Kong, China)

The latest demand of the community, which has changed dramatically in recent time, includes high-resolution displays (i.e. close to the human eye limits), low power consumption and undoubtedly the cost effective display and photonic devices. This is a big challenge for both scientists and engineers. The ferroelectric liquid crystal (FLC), because of the fast switching speed and low power consumption, is considered to be one of the potential candidates to serve as the building block for the modern devices. However, due to several limitations i.e. geometrical, optical and mechanical defects, these structures are less popular among the research and industrial regime. Recently, we have established that the Nano-scale photo-alignment technology could be used to improve characteristics of FLC systems. The photo-alignment, by different irradiance doses, offers good control on the anchoring energy and therefore provides good balance for elastic energy of the helix and the normalized anchoring energy. This balanced energy with proper selection of material parameter, that offer helix unwinding only in the presence of electric field i.e. ESHFLCs, offer high contrast ratio of >10K: 1 at the driving frequency of >3kHz.

By leveraging potentials of the Nano-scale photo-alignment and ESHFLCs, a concept for the field sequential color display (FSCD) has been developed that is characterized by the less power consumption, color triangle ~ 130% of NTSC and high contrast ratio. In addition to the FSCD some photonic elements have also been proposed that includes FLC grating, Fresnel lens, CD grating etc. Thus, these systems could find applications in variety of modern devices and modify the energy consumption statistics and image perceptions up to a large extent.

9182-43, Session 8

Topogical diversity of localized metastable states in chiral liquid crystals *(Invited Paper)*

Etienne Brasselet, Charles Loussert, Univ. Bordeaux 1 (France)

Liquid crystalline materials are well-known to exhibit various kinds of structural defects, whose space-variant optical properties are actually useful for a number of applications, including recently developed integrated optical vortex generators. In addition, since liquid crystal defects display well-defined topological features, their very existence also appears attractive in terms of information storage at the microscopic scale. An illustrative example is provided by frustrated chiral liquid crystals films, in which different localized metastable states can be written by either structured or unstructured light beams. We will present recent results regarding the controlled generation of multiple chiral topological states in liquid crystals.

9182-44, Session PWed

Photonic density of states of a stack of cholesteric liquid crystals and isotropic medium layers

Koryun B. Oganesyan, Yerevan Physics Institute (Armenia); Ashot H. Gevorgyan, Yerevan State Univ. (Armenia); Ruben V. Karapetyan, A. M. Prokhorov General Physics Institute (Russian Federation); Gagik A. Vardanyan, Nanoclusters, Nanomaterials & Nanoscience Inc. (United States); Yuri S Chilingaryan, E A Santrosyan, Yerevan State University (Armenia); Yuri V Rostovtsev, University of North Texas (United States)

We calculated the photonic density of states (PDS) of the eigen

polarizations (EPs) in the system composed of a stack of layers of a cholesteric liquid crystal (CLC) and an isotropic medium. The problem was solved by the layer addition modified method of Ambartsumian. The reflection spectra and photonic density of states (PDS) peculiarities, as well as the peculiarities of absorption and emittance were investigated. We obtained the dependences of the PDS as a function of parameters characterizing absorption and gain. It was shown that the subject system can be used in lasers for obtaining low threshold lasers with tunable emittance wavelength in wide ranges. It is shown that the subject system can work as a low threshold laser or a multi-position trigger.

9182-45, Session PWed

Dependence of the electrooptical properties of polymer-dispersed vertical aligned liquid crystals on the surface affinity of the liquid crystal and monomer

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We examined the effect of the surface affinity of the liquid crystal (LC) and monomer molecules on the electrooptical properties of the vertical aligned polymer-dispersed liquid crystals (PDLC). The liquid crystal molecules with greater contact angle on the surface formed more spherical LC droplet. On the other hand, the liquid crystal with smaller contact angle compared to the monomers resulted in cylindrical LC droplet. The PDLC sample with cylindrical LC droplet showed rapid increase of transmittance by applying the electric field and showed greater transmittance compared to the PDLC sample with spherical droplet. Threshold voltage of the spherical droplet was smaller than the cylindrical droplet sample.

9182-46, Session PWed

Effect of UV curing conditions on polymerized tunable chiral nematic liquid crystals

Mohammad Mohammadimasoudi, Jeroen Beeckman, Kristiaan Neyts, Univ. Gent (Belgium)

Chiral nematic liquid crystals (CLCs) have attracted substantial interest as they spontaneously self-organize to form a helical structure with no complex fabrication procedure required. As such they exhibit a reflection band for a certain wavelength interval Δ? (= ΔnP) with P the period and Δn the birefringence. Since the photonic band gap (PBG) can be tuned by applying external factors (heat, voltage, light, elasticity) CLCs are potentially interesting for large area optical filters and shutters, reflective displays and tunable lasers. The material that is used is a mixture of photopolymerizable and nematic LC including a chiral dopant. By selecting the appropriate chiral dopant concentration, it is possible to make devices for different operation wavelengths.

In this work, a device which consists of a mixture of photo-polymerizable liquid crystal, non-reactive nematic liquid crystal and a chiral dopant is fabricated. The influences of UV illumination on a partially polymerized chiral liquid crystal, are investigated. A blue wavelength shift of the photonic band gap is obtained as a function of intensity, duration time of UV illumination and the thickness of the cells. The shift is opposite to what is reported by others. Interestingly the width and depth of the photonic band gap is unaffected by the change in UV curing conditions, which indicates that there is no degradation by the UV light.

9182-47, Session PWed

On a photonic density of states of cholesteric liquid crystal cells

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The photonic density of states (PDS) of the eigen polarizations (EPs) in cholesteric liquid crystal (CLC) cells are calculated. The exact analytic expressions for the reflection and transmission matrices for the finite thickness CLC layer are used. We obtained the dependences for the PDS on the parameters characterizing absorption and gain, as well as the CLC cell thickness, CLC local dielectric anisotropy and CLC layer surrounding refractive index. The possibility of connections between the PDS and the density of the light energy accumulated in the medium are investigated and it was shown that these characteristics have analogous spectra and, besides, the influences of the problem parameters on these characteristics also were analogous. We have shown, that the decrement of the CLC layer surroundings refractive index leads to a sharp increase of the maximum PDS and, consequently, leads to a sharp decrement of the laser excitation threshold. The PDS dependence on the refraction coefficients of the substrates of the Fabry-Perot resonator filled with a CLC planar layer was investigated, too. It is shown that the subject system can work as a low threshold laser or a multi-position trigger.

9182-48, Session PWed

Optical, electro-optical, and dielectric spectroscopy of polymer stabilized ferroelectric liquid crystals

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Ferroelectric liquid crystals (FLCs) [1] have attracted a significant amount of attetion because of theire possible applications in fast switching devices. An application of FLCs that is only now being explored is optical imaging and recording. In this technology, a FLC material is placed between two conductor glass plates or transparent plastics. By applying an external electric field perpendicular to the electrodes, the coupling between ferroelectric polarization (electric dipole) and electric field was induced in the bulk of the cell [2, 3]. This causes an electric field to develop in the liquid crystal corresponding to the intensity of the light. The electric pattern can be transmitted by an electrode, which enables the image to be recorded. This technology is still being developed and is one of the most promising areas of FLC research. In recent years, Polymer Stabilized Ferroelectric Liquid Crystals (PSFLCs) [4-6] have been investigated in order to enhance and to improve their optic and electro-optic responses as well as their mechanic properties. These PSFLC materials, are also so-called "Composite materials", represent an exciting field of functional materials, providing a large range of emerging applications in display devices. To improve the electro-optical responses and mechanical properties of PSFLCs under applied electric field, great efforts have been made by several groups using different techniques. However, relatively few papers have been devoted to the dielectric spectroscopy. In this work, we present the linear dielectric relaxation characterizations of the pure FLC (0%) and PSFLCs with 4% and 8% polymer concentrations. In these studies, the linear dielctric permittivities can be determined, which allows to evaluate some physical parameters

of these materials, such as the twist elastic constant, elastic energy as well as the rotational viscosity. This study is also preceded, by using the optic microscopy analysis and electro-optic spectroscopy for all PSFLC systems investigated in this work.

Keywords: Ferroelectric liquid crystals, Polymer Stabilized Ferroelectric Liquid Crystals, Electro-optic, Dielectric properties

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9182-49, Session PWed

Dielectric and phase behaviors of a blue phase liquid crystal

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Dielectric spectra of a blue phase liquid crystal were acquired at various temperatures in conjunction with observations of optical transmission spectra and birefringent textures. The temperature-dependent dielectric data at 10000 Hz were specifically retrieved for further analysis. It was found that the second derivatives of the real-part permittivity with respect to the temperature sharply revealed the phase transitions of the liquid crystal on the cooling process from the isotropic phase through the chiral nematic phase.

9182-50, Session PWed

Effect of hybrid polyimides on electro-optical performance of optically compensated bend display mode

Guan-Jhong Lin, National Taiwan Univ. (Taiwan); Tien-Jung Chen, Bo-Rung Lin, Jin-Jei Wu, National Taipei Univ. of Technology (Taiwan); Ying-Jay Yang, National Taiwan Univ. (Taiwan)

Optically compensated bend liquid crystal (LC) cells are fabricated by using the hybrid polyimides, which are mixed and coated on the substrate surface as the alignment layer. The transmittance and phase retardation are both inversely proportional to the mixed concentration of polyimides. With the rigorous calculation and simulation, the relationship between the initial phase retardation and pretilt angle (PA) is obtained. In addition, the response behavior is sensitive to the PA, and the optimum value of the concentration ratio is founded. This study provides a method for designers to arbitrarily control the PA, and makes the well electro-optical performance.

9182-51, Session PWed

Dielectric characterizations of electroclinic effect near to N*-SmA-SmC* multicritical point

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Electro-optic and dynamic properties of three pure ferroelectric liquid crystals (FLCs) [1] materials (C10, C11 and C12) exhibiting chiral smectic C (SmC*)-smectic A (SmA)-cholesteric (N*) phases have been investigated in the present work. From electro-optic studies, the tilt angle and spontaneous polarization were determined as a function of temperature. In the dielectric measurements carried out without a dc bias field, we studied the soft-mode relaxation mechanism in the paraelectric SmA phase. From experimental data and using the theoretical Landau model around the N*-SmA-SmC* phase transitions, we evaluated the soft mode rotational viscosity and the electroclinic coefficient [2, 3]. The main result in this work, is that a relaxation process usually observed in the SmA phase is also observed in the cholesteric phase (N*) phase for two C10 and C11 materials [4] and it is interpreted as a soft-mode-like mechanism. This mechanism is related to the appearance of smectic order fluctuations within N* phase whose amplitude is increased when approaching the N*-SmA-SmC* multicritical point.

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9182-52, Session PWed

Fast-response Fabry-Perot wavelength-tunable filter using vertical-alignment polymer-stabilized liquid crystal with a curing voltage

Yan-Min Li, Wing-Kit Choi, National Taiwan Univ. (Taiwan)

Electro-optical properties of a Vertical-Alignment Polymer-Stabilized Liquid Crystal (VA-PSLC) cell are investigated. With a curing voltage, the strong scattering effect of VA-PSLC cell is much reduced, and a wavelength tunable filter (WTF) can be achieved as VA-PSLC cell is placed into a Fabry-Perot cavity. When a high curing voltage is applied, the LC molecules perform a large-angle-tilt alignment causing the wavelength tuning range to decrease, which is consistent with what we expected. Furthermore, the response speed of a VA-PSLC cell is significantly improved by the polymer effect. Such a WTF can have potential applications in telecommunication systems where high speed is desirable.

Conference 9183: Organic Light Emitting Materials and Devices XVIII

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9183-1, Session 1

Concepts for the material development for solution processable phosphorescent polymers and their application in PLEDs

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One example of organic electronics is the application of polymer based light emitting devices (PLEDs). PLEDs are very attractive for large area and fine-pixel displays, lighting and signage. The polymers are more amenable to solution processing by printing techniques which are favourable for low cost production in large areas. With phosphorescent emitters like Ir-complexes higher quantum efficiencies were obtained than with fluorescent systems, especially if multilayer stack systems with separated charge transport and emitting layers were applied in the case of small molecules. Polymers exhibit the ability to integrate all the active components like the hole-, electron-transport and phosphorescent molecules in only one layer. Here, the active components of a phosphorescent system - triplet emitter, hole- and electron transport molecules - can be linked as a side group to a polystyrene main chain. By varying the molecular structures of the side groups as well as the composition of the side chains with respect to the triplet emitter, hole- and electron transport structure, and by blending with suitable glass-forming, so-called small molecules, brightness, efficiency and lifetime of the produced OLEDs can be optimized.

By choosing the triplet emitter, such as iridium complexes, different emission colors can be specifically set. Different substituted triazine molecules were introduced as side chain into a polystyrene backbone and applied as electron transport material in PLED blendsytems. The influence of the alkyl chain lengths of the performance will be discussed. For an optimized blendsystem with an green emitting phosphorescent Ir-complex efficiencies of 60 cd/A and an lifetime improvement of 66.000 h @ 1000 cd/m2 were achieved.

9183-2, Session 1

Continuous synthesis of device-grade semiconducting polymers in droplet-based microreactors *(Invited Paper)*

John C. de Mello, Imperial College London (United Kingdom)

A method is reported for the controlled synthesis of device-grade semiconducting polymers, utilizing a droplet-based microfluidic reactor. Using poly(3-hexylthiophene) (P3HT) as a test material, the reactor is shown to provide a controlled and stable environment for polymer synthesis, enabling control of molecular weight via tuning of flow conditions, reagent composition or temperature. Molecular weights of up to 92 000 Da are readily attainable, without leakage or reactor fouling.

The method avoids the usual deterioration in materials quality that occurs when conventional batch syntheses are scaled from the sub-gram level to higher quantities, with a prototype five-channel reactor producing material of consistent molecular weight distribution and high structural order at a rate of ≈60 g/day. The droplet approach is especially well suited to the controlled synthesis of statistical and block co-polymers, providing greater control over stoichiometry than equivalent batch syntheses.

9183-3, Session 1

Polydopamine and melanin: nature's conjugated polymers *(Invited Paper)*

Alexander J. C. Kuehne, Tatjana Repenko, DWI an der RWTH Aachen e.V. (Germany)

Polydopamine can be oxidized to form melanin. Both polymers constitute high performance biological materials, which nature applies as universal adhesives, radical scavengers, and highly stable pigments. However, natural polydopamine and melanin are ill defined with regards to their molecular structure and melanin is highly crosslinked, which limits its solubility and therefore the chance for processing and application. I will present a facile synthetic method providing access to a linear and highly defined form of polydopamine via Kumada-coupling. The polymer can be converted into melanin by chemical and electrochemical oxidation. Polydopamine is exhibiting fluorescence in the blue spectrum, whereas the emission shifts to the near IR-spectrum after oxidation to melanin.

At the same time the controlled synthesis of linear polydopamine and melanin resolves a current dispute about the molecular structure of these polymers. Covalently and supramolecularly crosslinked networks as well as networks comprising dopamine trimers have been reported in synthetic systems. The procedure, which will be presented relies on Pd-catalyzed cross-coupling, yielding a strictly covalent linear polymer. The materials will help to resolve the current structural discrepancies observed in synthetic melanin and polydopamine materials.

9183-4, Session 1

The development of macromolecules for light-emitting diodes *(Invited Paper)*

Paul L. Burn, Ross D. Jansen-van Vuuren, Renjie Wang, Soniya D. Yambem, Shih-Chun Lo, Paul Meredith, Ebinazar B. Namdas, The Univ. of Queensland (Australia)

Innovation in materials has played a crucial role in development of organic light-emitting diodes, and most research has concentrated either on small organic molecules or conjugated polymers. We have pursued an alternative approach to materials for LEDs based on conjugated dendrimers. These molecules consist of a core, conjugated dendrons (branches) and surface groups, and by suitable choice of these components, efficient solution-processed LEDs can be made. In this presentation we will discuss light-emitting materials comprised of dendrimers. Such materials give insight into the effect of intermolecular interactions on the photophysical properties of phosphorescent materials. A combination of synthesis, physical, photophysical measurements, and device fabrication and testing will be described.

9183-5, Session 2

Development of new organic semiconducting materials for organic light-emitting diodes *(Invited Paper)*

Yun-Hi Kim, Gyeongsang National Univ. (Korea, Republic of)

Organic light-emitting diodes (OLEDs) are widely used as small size displays and are under development for large size television because of their advantages in emission with a wide viewing angle and color gamut. Phosphorescent emitters are used for green and red colors because of their high efficiency. The development of a deep blue emitter is especially important for displays, because the deep blue emission is more effective than normal blue to save energy when strong microcavity structures are adopted to enhance color purity. In order to develop the deep blue

emitter, we designed and synthesized anthracene-based florescent materials and Ir-based phosphorescent materials.

In this presentation, it will be reported synthesis and characterization of highly twisted anthracene derivatives with CIE of (0.155, 0.049) and deep-blue phosphorescent iridium complexes containing perfluorocarbonyl with CIE of (0.147, 0.116)

9183-6, Session 2

Efficient cyclometalated Pt complexes for displays and lighting applications *(Invited Paper)*

Jian Li, Arizona State Univ. (United States)

Photovoltaics and solid state lighting are examples of technologies that are enablers for a new sustainable energy economy, since these technologies would allow us to use a renewable energy source, and to use energy sources we already have more efficiently. The successful development of alternate low cost technology for current lighting devices will have a significant impact on the U. S. economy and national security. White organic light emitting diodes (OLEDs) with potentially high power efficiency are considered as strong candidate for the next generation of illumination devices. Moreover, the use of environmentally benign organic materials in white OLEDs and their potentially low fabrication cost makes them an attractive technological prospect. In this presentation, we will discuss our continuing efforts on the design, synthesis and characterization of novel platinum complexes for displays and lighting applications. The photo-physics, electrochemistry, electroluminescent properties and operational stability of these novel platinum complexes, including fluorine-free Pt-based deep blue emitters, will be discussed. The rational molecular design enables us to develop cyclometalated Pt complexes with both photon-to-photon (in thin film) and electron-to-photon (in device settings) conversion efficiency close to 100% for OLED applications. Our approaches to achieve high efficiency white OLED using a single emitter will be also included.

9183-7, Session 2

Bright coppertunities: efficient OLED devices with Cu(I)I-PyrPHOS-emitters *(Invited Paper)*

Manuela Wallesch, Karlsruhe Institute of Technology (Germany); Daniel Volz, Charlotte Fléchon, Daniel Zink, cynora GmbH (Germany); Stefan Bräse, Karlsruhe Institute of Technology (Germany); Thomas Baumann, cynora GmbH (Germany)

The mass market application of OLEDs is currently hindered because i) the materials are too expensive and contain rare metals such as iridium and ii) current processing techniques are elaborate and cannot easily be upscaled. Solution processable Cu(I)-complexes promise to solve both problems with one blow: Copper is an abundant metal, which offers new opportunities to develop materials for OLEDs. Due to their structural diversity, Cu(I) emitters allow for the design of materials with tunable properties. Beside this, it is also possible to adjust solution properties and introduce functionalities for cross-linking. The new materials feature exciting photophysical properties such as PLQY values close to unity and a tunable emission. The emission decay time is in the range of common emitters or lower, which is expected to reduce efficiency roll-off at high driving voltages.

Cu(I)-PyrPHOS-complexes also feature thermally-activated delayed fluorescence (TADF). As a consequence, they can make use of triplet and singlet excitons in a process called Singlet Harvesting, which paves the way for high efficiencies. Unlike Ir(III)-complexes such as Irppy3, triplet-triplet annihilation does not occur when using Cu(I), even in very high doping concentrations.

We demonstrate the feasibility of PyrPHOS-type Cu(I) complexes: We present strategies that enable a smart cross-linking process, where the Cu(I) emitters themselves play an important role. Also, we demonstrate high-brightness devices, which were operated at medium voltages, yielding 50.000 cd m-2. In a showcase example, we present a device with an external quantum efficiency greater than 20% with a solution processed Cu(I)-PyrPHOS-device without using outcoupling techniques.

9183-8, Session 2

Synthesis and electroluminescence properties of highly efficient dual core chromophores with side groups for blue emission *(Invited Paper)*

Jongwook Park, Hayoon Lee, Beomjin Kim, Seungho Kim, Joonghan Kim, Jaehyun Lee, Hwangyu Shin, The Catholic Univ. of Korea (Korea, Republic of)

Organic light-emitting diodes (OLEDs) based on organic small molecules are currently the subject of intense research efforts due to their promise in full-color large display applications. It is extremely difficult to produce highly efficient blue-light emitters with a long device lifetime because with a wide band gap their electronic levels are likely to be mismatched with the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) levels of the other OLED layers, such as the hole transporting layer (HTL) and the electron transporting layer (ETL).

We recently reported the syntheses of new dual core chromophore materials containing anthracene and pyrene (AP dual core) that exhibit high PL efficiencies. In this study, highly efficient blue emitting materials consisting of dual core derivatives with phenyl and/or naphthyl side groups and asymmetric or symmetric structures were designed and synthesized. The asymmetric structures 1-naphthalen-1-yl-6-(10-phenyl-anthracen-9-yl)-pyrene (Ph-AP-Na) and 1-(10-naphthalen-1-yl-anthracen-9-yl)-6-phenyl-pyrene (Na-AP-Ph), and the symmetric structures 1-phenyl-6-(10-phenyl-anthracen-9-yl)-pyrene (Ph-AP-Ph) and 1-naphthalen-1-yl-6-(10-naphthalen-1-yl-anthracen-9-yl)-pyrene (Na-AP-Na) were synthesized.

Of the synthesized compounds, Na-AP-Na was found to exhibit the highest EL device efficiency of 5.46 cd A-1. Ph-AP-Na, Na-AP-Ph, Ph-AP-Ph, and Na-AP-Na exhibit EL maximum values of real blue color in the range 455 nm to 463 nm. The y values of their color coordinates are within the range 0.125 to 0.142, so these compounds exhibit good blue color coordinates for displays. The lifetime of Na-AP-Na device showed more than three times longer than AP dual core (1-anthracen-9-yl-pyrene) device.

9183-9, Session 2

Unusually high efficiency in blue fluorescence OLEDs with large delta E (S1-T1) molecules *(Invited Paper)*

Yong-Jin Pu, Yamagata Univ. (Japan)

Deep-blue fluorescent compounds are particularly important in organic light-emitting devices (OLEDs). We synthesized an donor-accepotor (DA) type blue-emitting compound, 1-(10-(4-methoxyphenyl)anthracen-9-yl)-4-(10-(4-cyanophenyl)anthracen-9-yl)benzene (BD3). For comparison, a non DA type compound, 1,4-bis(10-phenylanthracene-9-yl)benzene (BD1) and a weak DA type compound, 1-(10-phenylanthracen-9-yl)-4-(10-(4-cyanophenyl)anthracen-9-yl)-benzene (BD2), were also synthesized. The twisted conformations of the two anthracene units in the compounds, confirmed by single crystal x-ray analysis, effectively prevent the π-conjugation, and the compound showed deep-blue photoluminescence (PL) with a high PL quantum efficiency, almost independent on the solvent polarity, resulted from the absence of intramolecular charge transfer state. The DA type molecule BD3 in a non-doped device exhibited a maximum external quantum efficiency (EQE) of 4.2% with a slight roll-off, indicating good charge balance due to the DA type molecular design. In the doped device with CBP host, the BD3 exhibited higher EQE than 10% with Commission International de L'Eclairge (CIE) coordinates of (0.15, 0.06) and a narrow full-width at half-maximum of 45 nm, which is close to the CIE of the High Definition Television standard blue. These results provide a molecular design concept leading to highly efficient deep-blue-emitting molecules for OLED applications.

9183-10, Session 3

Surface analytical investigation on organometal triiodide perovskite *(Invited Paper)*

Yongli Gao, Univ. of Rochester (United States)

In a little over a year, there has been an unexpected breakthrough and rapid evolution of highly efficient solid-state hybrid solar cells based on organometal trihalide perovskite materials. This technology has the potential to produce solar cells with the very highest efficiencies while retaining the very lowest cost. We have measured the electronic density of states of CH3NH3PbI3 using ultraviolet photoelectron spectroscopy (UPS), inverse photoemission spectroscopy (IPES), and x-ray photoelectron spectroscopy (XPS). The valence band maximum (VBM) and conduction band minimum (CBM) positions are obtained from the UPS and IPES spectra, respectively, by liner extrapolation of the leading edges. With the Fermi level close to the VBM, the sample is slightly p-type, with the EVBM=0.76 eV, ECBM=-0.9 eV, and transport energy gap 1.7 eV. The ionization potential (IP) of 6.16 eV can be obtained from the sum of the UPS measured EVBM and the work function of 5.40 eV. The XPS spectra reveal an obvious deficiency of N is, whereas the concentrations of I and Pb are close to the expected values. The existence of O and excessive C indicate that the surface is contaminated, and the contamination is reduced by 12-20% by thermal annealing in vacuum. The interface between CH3NH3PbI3 and TiO2 is also investigated. As CH3NH3PbI3 layer thickness increases, one sees a gradual shift of the vacuum level cut-off. At the CH3NH3PbI3 thickness of 8.2 nm, the shift saturates, signaling the end of the interface dipole formation. The evolution of the VB is even more gradual, and it appears to mature only at the thickest layer. Given the UPS probing depth of ~1.5 nm and the typical interface formation in other systems, the saturation of the vacuum level cut-off at 8.2 nm in CH3NH3PbI3/TiO2 is surprisingly large. It points at the possibility that the films are not truly uniform. On the other hand, the interface dipole of 0.7 eV CH3NH3PbI3 and TiO2 is important for further understanding of the energy level alignment and charge transfer across the interface.

9183-11, Session 3

Bulk transport and interfacial disorders of amorphous organic semiconductors in a thin film transistor configuration

Harrison Ka Hin Lee, Cyrus Yiu Him Chan, Shu Kong So, Hong Kong Baptist Univ. (Hong Kong, China)

Amorphous organic semiconductors are finding widespread applications in organic light-emitting diodes (OLEDs), lighting and display. Thus, there are numerous endeavors to develop new materials for OLED applications, and improving their intrinsic conductivities is of vital importance for the reduction of power consumption and device optimization. Here, we demonstrate organic thin film transistor (TFT) technique can be employed as a low-sample-demand tool for probing bulk transport properties of these amorphous organic semiconductors. Five different organic hole transporters (HTs) commonly used in organic light-emitting diodes are investigated. When these HTs are deposited on SiO2 gate dielectric layer, the TFT mobilities are 1–2 orders of magnitude smaller than those obtained from bulk films (3–8 micrometer) using time-of-flight (TOF) technique. The reduction of hole mobilities can be attributed to the interactions between the organic HTs and the polar SiO bonds on the gate dielectric layer. Detailed temperature dependence studies, employing the Gaussian disorder model, indicate that the SiO2 gate dielectric contributes between 60 and 90 meV of energetic disorder in the charge hopping manifold. Besides SiO2 gate dielectric, similar effects can also be observed for other polar insulators including polymeric PMMA and BCB, or HMDS-modified SiO2. However, when a common non-polar polymer, polystyrene (PS), is employed as the dielectric layer, the dipolar energetic disorder becomes negligible. Holes effectively experience bulk-like transport on the PS gate dielectric surface. TFT mobilities extracted from all five organic HTs are in excellent agreements with TOF mobilities. We also highlight that only a thin film down to ~10 nm is sufficient for TFT measurements. Thus our approach will be of special relevance to the evaluation of transport properties of newly synthesized materials in which the yield is yet to be optimized. The present study should have broad applications in the transport characterization of amorphous organic semiconductors.

9183-12, Session 3

Differences between vacuum-deposited and spin-coated amorphous films of OLED materials *(Invited Paper)*

Daisuke Yokoyama, Maki Shibata, Yamagata Univ. (Japan)

To realize low-cost fabrication processes for high-performance OLED displays and lighting panels, the understanding of solution-processed films and devices is becoming more important nowadays. However, differences between vacuum- and solution-processed films have not been sufficiently discussed, and they are sometimes regarded as identical. The properties of films in OLEDs are often symbolized only by the names of materials without considering how they are fabricated and how molecules are oriented [1] and condensed in them.

In this presentation, we will show and discuss the important differences between physical properties of vacuum-deposited and spin-coated films of small-molecule OLED materials, especially focusing on the differences in film densities and molecular orientation. Using some techniques such as ellipsometry, X-ray reflectivity, and dissolved film's absorption measurements, we carefully determined the absolute densities and packing coefficients of (a) single crystals, (b) vacuum-deposited amorphous films, and (c) spin-coated amorphous films (after a baking process) of small-molecule OLED materials. We obtained the results of (a)>(b)>(c) for commonly used OLED materials. This result demonstrates a fundamental difference between vacuum- and solution-processed films, and seems analogous to the fact that vacuum-deposited films have higher densities than films formed from a melted liquid [2]. In addition, we monitored the change of the densities of spin-coated films during baking processes, and found that apparent densities of thin layers are tend to be low. Since the differences in film densities and molecular orientation are fundamental factors affecting both electrical and optical properties of amorphous films used in OLEDs, we should consider their differences carefully when discussing device performances in detail.

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9183-13, Session 3

Effect of molecular orientation in OLED electron and hole transport layers and its effect on device performance

Kenneth L. Kearns, The Dow Chemical Co. (United States); Hong-Yeop Na, The Dow Chemical Co. (Korea, Republic of); Hunter Woodward, Dean M. Welsh, Timothy De Vries, David Devore, Peter Trefonas III, Liang Hong, The Dow Chemical Co. (United States)

Recent progress has shown that molecular orientation in vapor-deposited glasses can affect device performance. The deposition process can result in films where the glass material is preferentially ordered normal to the plane of the substrate. Materials made within Dow's Electronic Materials business show enhanced performance when the orientation

of the glass, as measured by spectroscopic ellipsometry, is high as compared to other materials. In addition, the density of the as-deposited films is approximately 1% greater than what can be realized from slowly cooling the supercooled liquid. This density difference is quite large given that the density difference between glasses and crystals is approximately 5% for organics. This enhanced density may also play a role in device performance.

9183-14, Session 4

Recent developments in optically and electrically detected magnetic resonance (ODMR and EDMR, respectively) of luminescent π-conjugated materials and OLEDs *(Invited Paper)*

Joseph Shinar, Iowa State Univ. (United States); Ying Chen, Univ. of Florida (United States)

It is widely recognized that nonradiative quenching of excitons by other excitons and polarons become the dominant decay mechanism of these excitons at high excitation densities. These quenching processes cause the roll-off in the efficiency of OLEDs and prevent lasing at high injection current densities. This review presents the ODMR evidence for these PL- and EL-quenching processes, in particular the latest evidence that these quenching processes can also account for the microwave-chopping frequency dependence of the resonance. Most importantly, it reveals the central role of the strongly spin-dependent annihilation of triplet excitons (TEs) by polarons, since under normal excitation conditions the steady-state polaron and TE populations are 100 – 10,000 times the singlet exciton (SE) population. In addition, it also suggests that quenching of SEs by bipolarons, likely stabilized by a counterpolaron or countercharge at specific sites, may also be a significant quenching mechanism that also affects the charge transport properties.

9183-15, Session 4

Degradation of blue phosphorescent organic LEDs analyzed by solution NMR spectroscopy *(Invited Paper)*

Tatsuya Fukushima, Hajime Suzuki, Kyoto Univ. (Japan); Hiroto Ito, Shinya Ootsu, Kunimasa Hiyama, Hiroshi Kita, Konica Minolta, Inc. (Japan); Hironori Kaji, Kyoto Univ. (Japan)

Although the performance and lifetime of OLEDs have been steadily improved, the lifetime of blue OLEDs are still short compared with that of green and red OLEDs. For example, the lifetime of blue OLEDs using FIrpic as a phosphorescent emitter is relatively short, although the device can attain high external quantum efficiency by the use of singlet and triplet excitons. To improve the lifetime of the blue phosphorescent OLEDs, it is important to clarify degradation mechanisms. Generally, solution NMR spectroscopy is useful to identify the chemical structures of organic molecules. Therefore, organic materials in OLEDs can be analyzed including the decomposition. The analysis of device degradations by solution NMR is considered to have following advantages; 1) direct experimental evidence is obtained on the decomposition of organic molecules, 2) several kinds of molecules in multi-layered OLEDs can be analyzed distinctively, and 3) the amount of degraded molecules can be quantified. In this study, we have investigated material degradations in FIrpic-based blue phosphorescent OLEDs by solution NMR. From the experiments, we found that decomposition occurs for TPhDB (and CDBP) molecules, which is used as an electron-transporting material (and host material), in OLEDs during driving the device. The material degradation is considered to be related to the device degradation.

9183-16, Session 4

Exciton-induced degradation of interfaces in OLEDs and other organic optoelectronic devices *(Invited Paper)*

Hany Aziz, Qi Wang, Graeme M. Williams, Yingjie Zhang, Univ. of Waterloo (Canada)

The limited performance stability and gradual loss in the electroluminescence efficiency of OLEDs when under electrical stress continues to be a challenge. Although a number of degradation mechanisms associated with chemical and physical changes that occur in the organic layers and electrodes have been identified, the role of inter-layer interfaces in the electrical aging behavior of OLEDs has been unclear. We recently found that organic/electrode interfaces in OLEDs and other organic optoelectronic devices are extremely susceptible to degradation by excitons. This interfacial degradation is found to be photochemical in nature and results in a deterioration in charge injection. More recently we found that organic/organic interfaces are similarly susceptible to degradation by excitons, but only when a high concentration of charges is present near the interface. The results uncover the higher susceptibility of interfaces in comparison to bulk materials to degradation by exciton-polaron interactions, a behavior that appears to play a role in the gradual loss in OLED efficiency. Further work has shown that exciton-polaron interactions at organic/organic interfaces induce molecular aggregation, a behavior found to occur in a wide range of materials commonly used as emitter hosts in fluorescent and phosphorescent OLEDs. This previously unknown interfacial aggregation behavior is more severe in wider band-gap materials, suggesting it may be behind the lower stability of blue and phosphorescent OLEDs in general. Results related to this newly discovered interfacial degradation mechanism in OLEDs will be presented.

9183-17, Session 4

Theoretical investigation of the degradation mechanisms in host and guest molecules used in OLED active layers

Paul Winget, Minki Hong, Jean-Luc Brédas, Georgia Institute of Technology (United States)

A feature of organic light-emitting diodes (OLEDs) that has to date received little attention is the prediction of the stability of the molecules involved. Here we present computational results intended to aid in the development of stable systems by identifying major degradation pathways and defining new design strategies to provide an a priori guide to the synthesis of stable materials for OLED applications for both phosphorescent emitters and organic host materials. The chemical reactivity of these molecules in the active layers of the devices is further complicated by the fact that, during operation, they can be either oxidized or reduced (as they localize a hole or an electron) in addition to forming both singlet and triplet excitons. It is difficult to estimate the reaction rates from thermodynamic quantities since the reaction barriers for the various chemical processes on each of the potential energy surfaces for the ionic and excited states can be radically different, leading to different qualitative predictions even within an homologous series of host or guest molecules. We compare the barriers for Ir-N and Ir-C bond cleavage in a series of substituted iridium(III) complexes and carbon-heteroatom bond cleavage for a collection of ambipolar host materials. We find that the dissociation barriers and the triplet energy of both host and guest materials can be modified using different chemical modifications. The implications for optimization of materials lifetime will be discussed.

9183-18, Session 4

Improving the lifetime of the solution-processed organic light-emitting diodes by alleviating solvent effect and interfacial degradation

Shuyi Liu, Ying Chen, Franky So, Univ. of Florida (United States)

With comparable efficiencies as the thermal evaporated phosphorescent organic light emitting diodes (OLEDs), solution processed OLEDs are interesting with their great potential in lowering the fabrication cost. However, there is hardly any systematic report on their lifetimes. In this study, we focus on improving the stability of the solution-processed phosphorescent green OLEDs by dealing with two dominant factors limiting the device lifetime: the solvent effect on the film quality and the interface between the emitting layer (EML) and the hole injection/transport layer (HIL/HTL). By choosing the emitting system composed of high glass transition temperature (Tg) materials, a high annealing temperature is applied to remove the residue solvent and improve the film quality, which leads to enhanced device stability. The lifetime of the device is further improved by replacing the solvent in the precursor, which has a direct impact on the molecular packing density of the films. Different interfaces between the solution-processed EML and preceding layers are also studied, with the results showing that with our solution-processed p-type nickel oxide (NiOx) HTL, the devices have the longest lifetime due to the stable hole injection/electron blocking interfaces formed between NiOx and EML. As a result, we are able to prolong the lifetime of our solution-processed phosphorescent green OLEDs. Our study offers a potential solution to extend the lifetime of solution-processed OLEDs.

9183-20, Session 5

The photophysics of intramolecular charge transfer molecules and TADF: effects of CT singlet triplet coupling *(Invited Paper)*

Andrew P. Monkman, Durham Univ. (United Kingdom)

Detailed photophysical measurements of intramolecular charge transfer states have been made both in solution and solid state. Temperature dependent emission and delayed emission are used to map the energy levels involved in molecule decay, and through detailed kinetic modelling of the thermally activated processes observed, energy barriers between these states determined.

For well defined molecules locked in specific donor acceptor configurations, the CT states are found to be the lowest lying excited states with very small electron exchange energies. In these cases the decay kinetics of the molecules become significantly different to normal molecules. When the local excitonic triplet state also lies close to the CT states the photophysics becomes yet more complex. These various contributing pathways will be elucidated.

In solid state we find that isolation of the ICT molecules, with no access to excited state hopping through the surrounding matrix greatly changes the photophysics. Quantum yields increase markedly, the relative energy positions of the excited states alter as compared to those seen in solution state. Time dependent delayed emission measurements reveal very different temperature dependent natures and the effects of ICT emitter inhomogeneity is revealed. However, the details of the TADF or E-type delayed emission can be described and estimates on the efficiency of the process made. Clear evidence will be given to show that TADF reaches 100% efficiency at harvesting triplet states, and device having > 15% EQE at moderate brightness levels will be discussed.

9183-21, Session 5

Host engineering for high quantum efficiency in green thermally activated delayed fluorescent device *(Invited Paper)*

Yirang Im, Bo Seong Kim, Oh Young Kim, Jun Yeob Lee, Dankook Univ. (Korea, Republic of)

The external quantum efficiency of thermally activated delayed fluorescent device was improved by developing host materials for the delayed fluorescent emitters. Bipolar host materials and mixed host structure were used as the host material for the thermally activated delayed fluorescent material for efficient energy transfer, charge balance and exciton confinement. Optimized host material for the thermall activated delayed fluorescent material enabled the fabrication of highly efficient fluorescent device with quantum efficiency above 20%.

9183-22, Session 5

TADF for singlet harvesting: next generation OLED materials based on brightly green and blue emitting Cu(I) and Ag(I) compounds *(Invited Paper)*

Hartmut Yersin, Markus J Leitl, Rafal Czerwieniec, Univ. Regensburg (Germany)

For high-efficiency OLEDs, it is essential that all generated excitons are harvested and transferred into light. In this respect, use of conventional organic molecules is limited, since they can exploit only 25 % of the excitons. Thus, the mechanism of triplet harvesting has been developed. It is based on phosphorescent metal complexes that, due to high spin-orbit coupling (SOC) induced by the metal centers, show efficient and short-lived triplet state emission. However, these complexes contain rare and expensive metals (Ir, Pt). Although these materials are already successfully applied, they exhibit some further shortcomings, such as problems with blue-light emission. Therefore, a new mechanism for light generation in OLEDs, the singlet harvesting mechanism, has been proposed.[1] It is based on the molecular effect of a thermally activated delayed fluorescence (TADF)[2]. Only by this mechanism, which is governed by an allowed emission from the lowest excited singlet state, it becomes possible to apply low-cost materials. In particular, Cu(I) and Ag(I) compounds have a number of further advantages, such as realizability of blue-light emitters, prevention of concentration quenching, and achievability of short emission decay times at almost 100 % TADF quantum yields.[1,3] In this presentation, the discussed mechanisms will be explained on an introductory level and case studies will be presented showing a wide tunability of photophysical properties of Cu(I) and Ag(I) based emitters.

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9183-23, Session 5

Unusual photoemission by lower photon energy than ionization energy for organic EL materials with giant surface potential *(Invited Paper)*

Hiroumi Kinjo, Hyunsoo Lim, Yusuke Ozawad, Tomoya Sato, Yasuo Nakayama, Hisao Ishii, Chiba Univ. (Japan)

Organic EL materials often show spontaneous orientation polarization in evaporated films with giant surface potential (GSP). This polarization, which induces interface charge at organic/organic hetero-junction in organic EL devices, significantly affects the device performance. In this study, by using low energy ultraviolet photoemission spectroscopy (LE-UPS) and photoelectron yield spectroscopy (PYS), we have found unusual photoemission from films of Alq3 and 4CzIPN with GSP. Even if the photon energy is smaller than their ionization energy, photoelectrons are clearly observed. For example, the ionization energy of Alq3 is about 5.6eV, but we observed that PYS spectrum has a threshold around 2.8eV, and LE-UPS indicates the existence of some states 2eV above the Fermi level of the substrate. Alq3 shows the positive GSP with the positively charged surface. If we use a derivative of Alq3, Al(7-prq)3, in which three propyl groups are attached to the three ligands, the polarity of the GSP is reversed, and there exist negative charges at the surface in contrast to Alq3. So, the surface can capture not negative carriers but positive carriers. For Al(7-prq)3, the unusual photoemisson was not observed. From these results, we suggest that the observed unusual photoemission is ascribed to photoemission from negative carriers which are captured only for Alq3 film. (We expect that photoemission from positive carriers in Al(7-prq)3 should be included in PYS and LE-UPS, but the ionization energy of cation is larger than that of the neutral molecule, inducing no additional lower energy photoeimission. Usually electron affinity has been observed by inverse photoemission spectroscopy (IPES), in which radiation damage and poor energy resolution are serious problem. Our finding can be extended to develop as a method to determine electron affinity of various organic EL materials with high resolution and less damage. Because these anion states are fully relaxed in the film, the obtained electron affinity is more suited value to discuss the carrier states in devices, while the carrier states are not well relaxed in the case of IPES. In the presentation, the result for 4CzIPN, which has attracted much attention due to thermally activated delayer fluorescence, will be discussed.

9183-24, Session 6

Langevin and trap assisted recombination in small molecular based phosphorescent OLEDs (PhOLEDs)

Jeong-Hwan Lee, Sunghun Lee, Seung-Jun Yoo, Kwon-Hyeon Kim, Jang-Joo Kim, Seoul National Univ. (Korea, Republic of)

Understanding of the charge carrier recombination process and the emission of photons from excitons is of great importance to OLEDs, because these properties are intimately related to the performance of these devices. Unfortunately, little fundamental research has been undertaken into this issue in PhOLEDs. In this study, Langevin and trap-assisted recombination mechanisms were determined and investigated in small molecule-based PhOLEDs by using two different hosts; one with a single host, 4,4'-Bis(carbazol-9-yl)biphenyl (CBP), and the other with an exciplex-forming co-host. The recombination types of the PhOLEDs were directly determined in the diffusion dominated current region using the Shockley diode equation. As a result, it was determined that the Langevin recombination and energy transfer process are dominant over trap-assisted recombination in the green PhOLED with the exciplex forming co-host system. In contrast, trap-assisted recombination is dominant in the PhOLED with the single host. Based on the analysis of transient electroluminescence and capacitance-voltage measurements, it was clearly demonstrated that the accumulated charge density is lower in the exciplex forming co-host based PhOLED than in the single host based PhOLED. Low charge density in the PhOLEDs in the exciplex forming host must be related to the low efficiency roll-off caused by reduced exciton-polaron quenching.

9183-25, Session 6

Device design for optimal exciton harvesting *(Invited Paper)*

Zhenghong Lu, Univ. of Toronto (Canada)

Organic light emitting diodes (OLEDs) show potential as the next generation solid state lighting technology. A major barrier to widespread adoption at this point is the efficiency droop that occurs for OLEDs at practical brightness (~ 5000 cd/m2) levels necessary for general lighting. We highlight recent progress in highly efficient OLEDs at high brightness, where improvements are made by managing excitons in these devices through rational device design. General design principles for both white and monochrome OLEDs are discussed based on recent device architectures that have been successfully implemented.

9183-26, Session 6

Exciplex forming co-hosts for efficient fluorescent and phosphorescent OLEDs *(Invited Paper)*

Jang-Joo Kim, Seoul National Univ. (Korea, Republic of)

The exciplex forming system can be considered to be a quasi-host that has its HOMO and LUMO levels as the HOMO of the hole transport material (donor) and the LUMO of the electron transport material (acceptor). In addition, its triplet energy level is almost the same as that of the singlet, meaning that we can select a quasi-host such that its HOMO-LUMO gap is very close to the phosphorescent dopant. These characteristics of the co-host can be utilized to achieve high efficiency and low driving voltage in OLEDs. In this talk, we will present highly efficient phosphorescent OLEDs using various exciplex forming co-hosts with EQEs' over 30%. Highly efficient fluorescent OLEDs will also be reported.

9183-27, Session 6

Engineering efficiency roll-off in organic light-emitting devices *(Invited Paper)*

Russell J. Holmes, Univ. of Minnesota, Twin Cities (United States)

While capable of realizing very high peak efficiency, many organic light-emitting devices (OLEDs) suffer a significant reduction (or roll-off) in efficiency under large injected current densities. This can often limit device brightness and compromise operational stability. Much previous work has identified the key contributing factors to the efficiency roll-off in phosphorescent OLEDs as triplet-triplet annihilation and triplet-polaron quenching. Here, the parameters associated with these quenching processes are independently measured, and the impact of the exciton recombination zone width on the quenching processes in various OLED architectures is examined directly. In devices employing a graded-emissive layer (G-EML) architecture the efficiency roll-off is due to both triplet-triplet annihilation and triplet-polaron quenching, while in devices which employ a double-emissive layer (D-EML) architecture, the roll-off is dominated by triplet-triplet annihilation. Overall, the efficiency roll-off in G-EML devices is found to be much less severe than in the D-EML device. This result is well accounted for by the larger exciton recombination zone that is experimentally measured in G-EML devices, serving to reduce exciton density-driven loss pathways. Indeed, a predictive model of the device efficiency based on the quantitatively measured quenching parameters shows the role a large exciton recombination zone plays in mitigating the roll-off.

9183-28, Session 6

Circularly polarized light emitting OLEDs via a solution-processed electroluminescent polymer: chiral small molecule blend *(Invited Paper)*

Alasdair J. Campbell, Ying Yang, Rosenildo Correa da Costa, Imperial College London (United Kingdom); Detlef M. Smilgies, Cornell Univ. (United States); Matthew J. Fuchter, Imperial College London (United Kingdom)

Circularly polarized (CP) light emitting devices have enormous potential in a wide range of applications including highly efficient LCD backlights to optical quantum information processing, however to date, attempts at generating CP-electroluminescence (EL) from polymer based organic light emitting diodes (P-OLEDs) have involved either complex and bulky device architectures or custom synthesized non-standard polymers. Here we show that by simply doping a conventional light emitting polymer poly[9,9-dioctylfluorene-co-benzothiadiazole] (F8BT) with an intrinsically chiral ortho-fused aromatic molecule, known as a helicene, we are able to generate substantial levels of CP-EL directly (Advanced Materials 25, pp 2624-2628 (2013)). Both photoluminescent and electroluminescent emission from the polymer is observed to become significantly circularly polarized, with the sign of the CP emission directly determined by the handedness of the helicene dopant. This effect is independent of film thickness and appears to involve a unique crystalline phase. We believe this easily translatable and simple approach to fabricating CP light emitting devices will have a significant impact on display and photonic technologies.

9183-29, Session 7

Towards highly transparent conducting electrodes for organic flexible devices *(Invited Paper)*

Illhwan Lee, Sungjun Kim, Juyoung Ham, Bola Lee, Jong-Lam Lee, Pohang Univ. of Science and Technology (Korea, Republic of)

In this work, we present a novel way in fabricating flexible transparent electrodes with designing the multilayer system using optical simulation. We calculated the transmittance of TiO2 (n=2.5)/Graphene (3 layer)/WO3 (n=1.9) structure by matching the dielectric constant of each materials. Using this TiO2/Graphene (3 layer)/WO3 multilayer structure, the transmittance in the visible region increased from 85 % to 92 %. The organic light emitting diodes (OLEDs) using the multilayer structured graphene as a transparent anode had 23 % greater luminance than the device using ITO. And by controlling the surface energy of substrate by oxygen plasma treatment, the growth mode of thin Ag film can be controlled and thereby thin Ag layer leads to significantly improved growth homogeneity of the Ag layer. When employing pretreatment, the transmittance of thin Ag film is increased and sheet resistance is markedly reduced. By reducing the Ag thickness (< 10 nm), we can design the highly transparent metal/dielectric structure. Employing this smooth and ultra-thin Ag/WO3 as a transparent electrode, a highly optical transmittance due to reducing the localized surface plasmons in visible wavelength and low sheet resistance were achieved, leading to the improvement of OLEDs performance. Furthermore, employing the soft materials such as Ormoclear instead of inorganic dielectrics, Ormoclear/Ag/WO3 (OAW) films show the excellent transparency independent of film thickness. OAW exhibits the low sheet resistance (4.8 ohm sq-1), high transmittance as high as 91.8 % and enhanced efficiency of 7.63 % of OSCs compared to those with ITO electrode. Moreover, the well-ordered nano-patterned OAW with a dimple diameter of 90 nm was prepared using nano-imprint lithography, leading further increase in photo-current density and thereby improve the power conversion efficiency by 13%.

9183-30, Session 7

Highly efficient flexible organic light emitting diodes *(Invited Paper)*

Qibing Pei, Lu Li, Jiajie Liang, Charlotte Chou, Xiaodan Zhu, Xiaofan Niu, Zhibin Yu, Univ. of California, Los Angeles (United States)

The light extraction efficiency of OLEDs from the exciton radiative decay is limited to less than 30% due to plasmonic quenching on the metallic cathode and waveguide in the multi-layer sandwich structure. We report the synthesis of a flexible nanocomposite electrode comprising single-walled carbon nanotubes, silver nanowires, and barium strontium titanate nanoparticles. Green polymer OLED fabricated on the nanocomposite electrode exhibit a maximum current efficiency of 118 cd/A at 10,000 cd/m2 with the calculated external quantum efficiency being 39%. The efficiencies of white PLEDs are 47 cd/A and 30%, respectively. The devices can be bent to 3 mm radius repeatedly without significant loss of electroluminescent performance. The nanocomposite electrode could pave the way to high-efficiency flexible OLEDs with simplified device structure and low fabrication cost.

9183-31, Session 7

Utilizing PEDOT:PSS as a versatile conductive low-index layer for efficiency improvement in OLEDs *(Invited Paper)*

Seunghyup Yoo, Hyunsu Cho, Eunhye Kim, KAIST (Korea, Republic of)

The efficiency of organic light-emitting diodes (OLEDs) is often limited by various loss channels such as excitation of waveguided modes or surface plasmon polariton (SPP) modes. To realize highly efficient OLEDs, it is thus important to develop a structure that prevents or reduces coupling to these modes . Note that OLEDs can be modeled optically as a multilayer thin-film stack. Conventional approach to tuning the optical property of such a thin-film structure has been to add or insert layers with a different refractive index. Hence it may be useful if there is a material that has a refractive index different from that of organic layers. Furthermore, one may be able to have a larger degree of freedom in optical design if such a layer has conducting properties. In this respect, we focus on the fact that PEDOT:PSS – the most commonly used conducting polymer in organic electronics – has a refractive index lower than most organic semiconductors and study on how to utilize such properties to improve the performance of OLEDs.

First, an outcoupling enhancing structure is introduced in which PEDOT:PSS covers micropatterned ITO electrodes so that an index contrast can allow for extraction of waveguided modes. Then, a polarizer-free high contrast-ratio OLED is presented in which the low refractive index of PEDOT:PSS results in the enhanced efficiency with little impact on the overall reflection of ambient light. Detailed enhancement mechanisms are elucidated by the full wave-optic analysis that takes into account dipole emission and excitations to waveguided and SPP modes.

9183-32, Session 7

Universal flexible polymeric anodes for simplified organic optoelectronics *(Invited Paper)*

Su-Hun Jeong, Seong-Hoon Woo, Tae-Hee Han, Min-Ho Park, Tae-Woo Lee, Pohang Univ. of Science and Technology (Korea, Republic of)

To set up a true ubiquitous environment, the optoelectronic devices, such as solar cell, touch screens, and displays, should be not only be portable; they must be able to change their shapes freely. In other word,

these optoelectronic devices should be flexible. In order to embody fully flexible optoelectronic devices, conventional transparent anode materials represented by indium-tin oxide (ITO) should be replaced with any other flexible anode materials due to its brittleness. Furthermore, the increasing price due to scarcity of indium makes it difficult for its use in low-cost, large-area optoelectronics. Here, we embodied ITO-free organic optoelectronic devices including organic light-emitting diodes (OLEDs) and organic photovoltaic cells (OPVs) using self-organized conducting polymers as transparent anodes without any hole injection layer (HIL) in OLEDs or hole extraction layer (HEL) in OPVs.

The self-organized conducting polymers are prepared based on poly(3,4-ethylenedioxythiophene):poly(4-styrenesulfonate) (PEDOT:PSS) in which 5wt% DMSO is added to enhance their conductivity. As a key component, perfluorinated polymer (PFI) is included to achieve a high work function and hydrophobicity by inducing surface-enriched PFI layer. They showed excellent tuning of work-function. The maximum work-function of the anode is 5.8 eV which is the highest value among the flexible anodes which have been reported until now. Moreover, transparency is higher than 90 % in all the visible range. Our green phosphorescent OLEDs (PhOLEDs) based on our polymeric anodes showed extremely high current efficiency CE (~128 cd/A) even with a simplified structure compared to conventional ITO/polymeric HIL(PEDOT:PSS) devices (CE ~128 cd/A). Furthermore, we analyzed hole-injection characteristics between the modified polymeric anode layer and a hole-transport layer using dark injection space-charge limited current (DI-SCLC) measurement. Besides PFI, an additional fluorinated polymer, poly(styrenesulfonate-pentafluorostyrene) copolymer (P(SSNa-co-PFS)) further improved the CE (~139 cd•A-1) of green PhOLEDs, which is the highest CE among reported polymeric anode-based flexible OLEDs. We finally demonstrated large-area ITO-free flexible solid-state lighting devices using white fluorescent OLEDs.

To demonstrate another optoelectronic device application of our polymeric anodes, we also fabricated OPVs on our polymeric anodes. The OPVs based on our polymeric anode without HEL exhibited power conversion efficiency PCE ~5.5 %, which is comparable to that of conventional ITO/polymeric HEL (PEDOT:PSS)-based OPV (PCE ~5.4 %).

9183-34, Session 8

Light-emitting electrochemical cells by gravure printing: from ink formulation to device

Gerardo Hernandez-Sosa, Serpil Tekoglu, Ralph Eckstein, Sebastian Stolz, Karlsruher Institut für Technologie (Germany); Manuel Hamburger, Ruprecht-Karls-Univ. Heidelberg (Germany); Norman Mechau, Uli Lemmer, Karlsruher Institut für Technologie (Germany)

Printing or coating functional inks by means of roll-to-roll compatible techniques is expressed as an almost universal motivation in publications dealing with solution processed organic electronics. However, in the race for improving device performance, the study of the material processability by high throughput techniques has usually been overlooked.

In this work we present the case of gravure printed light-emitting electrochemical cells (LECs) to exemplify the compromises between printability and performance when moving away from the laboratory scale towards the fabrication of organic optoelectronics devices by high throughput techniques. LECs represent a technology with distinct processing advantages over organic light-emitting diodes since they are comprised of one single active layer and prescind from low work-function cathodes. The current development of LECs places them as a promising candidate for the large area production of lighting, packaging or signing applications [A. Sandström, et al Nat. Comm. 2012, 3, 1002]. The presented approach shows that a polymer based LEC system would offer the possibility of developing ink formulations for a given printing technique without changing its chemical composition or the need of additives. The materials used for the ink formulation were characterized by cyclic voltammetry. Moreover, the suitability of the formulations to the gravure printing technique was assessed by rheological measurements. The optimized formulation yielded gravure printed devices with a maximum luminance of ~2000cd/m^2 and a shelf lifetime over six months.

9183-35, Session 8

Fabrication of the 14 inch OLED prototype by inkjet printing process *(Invited Paper)*

Ze Liu, Gang Wang, Qing Dai, Hui-Feng Wang, Hui-Ting Shih, Ying Cui, Shou-Lei Shi, Jing-Wen Yin, Rui Xu, Chen Zhang, Yong-Wei Tu, BOE Technology Group Co., Ltd. (China)

Organic light-emitting diodes (OLEDs) have drawn much attention because of their potential applications in flat-panel displays and solid-state lightings, products using OLEDs technology have been successfully developed and have been commercialized during last few years by the effort of material, equipment and panel makers. Organic film formation is a key process for OLEDs, two approaches have being applied now, one is the conventional thermal vapor method under vacuum and the other one is immature solution method under ambient conditions. Compared to the thermal vapor deposition process, advantages like process without fine metal mask, higher material usage and fewer vacuum process, solution process has become one of potential technology for large size OLED production. In this report, the control of film quality and profile in OLED devices has been studied, especially the baking condition and bank properties. According to the results, a 14 inch OLED prototype by inkjet printing with resolution of 80 ppi was fabricated and shown.

9183-36, Session 8

Towards fully spray coated organic light emitting devices

Koen Gilissen, Jeroen Stryckers, Jean Manca, Wim Deferme, Univ. Hasselt (Belgium)

Pi-conjugated polymer light emitting devices have the potential to be the next generation of solid state lighting. In order to achieve this goal, a low cost, efficient and large area production process is essential. Polymer based light emitting devices are generally deposited using techniques based on solution processing e.g.: spin coating, ink jet printing. These techniques are not well suited for cost-effective, high throughput, large area mass production of these organic devices. Ultrasonic spray deposition however, is a deposition technique that is fast, efficient and roll to roll compatible which can be easily scaled up for the production of large area polymer light emitting devices (pLEDs). This deposition technique has already successfully been employed to produce organic photovoltaic devices (OPV) [1]. Recently the electron blocking layer PEDOT:PSS [2] and metal top contact [3] have been successfully spray coated as part of the organic photovoltaic device stack. In this study, the effects of ultrasonic spray deposition of polymer light emitting devices is investigated. For the first time, spray coating of the active layer in pLED is demonstrated. Different solvents are tested to achieve the best possible spray-able dispersion. The active layer morphology is characterized and optimized to produce uniform films with optimal thickness. Furthermore these ultrasonic spray coated films are incorporated in the polymer light emitting device stack to investigate the device characteristics and efficiency. Our results show that after careful optimization of the active layer, ultrasonic spray coating is prime candidate as deposition technique for mass production of pLEDs.

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9183-37, Session 8

Fully solution processed, white emitting tandem OLEDs

Stefan Höfle, Alexander Schienle, Christoph Bernhard, Uli Lemmer, Alexander Colsmann, Karlsruher Institut für Technologie (Germany)

Organic light emitting diodes (OLEDs) can be fabricated either from solution or by vacuum deposition. The latter allows for stacking an arbitrary number of functional layers, such as charge carrier transport or blocking layers. This in turn allows a much better charge carrier confinement within the active layer and hence a higher device efficiency and lifetime. On the other hand, the solution deposition of organic semiconductors features low-cost coating and printing processes. Due to solvent limitations, however, the application of multi-layer device architectures from solution remains very challenging, consequently limiting efficiency and lifetime of the respective devices. One of the most crucial degradation mechanisms in OLEDs is a high operation device current. A promising concept to reduce the device current while at the same time preserving the luminance is to stack two or more OLEDs on top of each other and hence to generate multiple photons from one injected electron-hole pair. In order to monolithically stack two OLEDs it is necessary to design an intermediate contact, commonly referred to as charge generation layer (CGL), which enables an efficient charge carrier generation and injection into the adjacent emission layers. In this work we present fully solution processed Tandem-OLEDs in inverted device architecture. Incorporating the emitter polymer Super Yellow in both OLEDs allows for the fabrication of efficient monochromatic Tandem-OLEDs while the combination of a blue and an orange emitting polymer enables white emitting Tandem-OLEDs. The CGL comprises solution deposited tungsten oxide (WO3) for the injection of holes into the bottom OLED. For electron injection into the top OLED we utilize ZnO which is modified by an ultra-thin polyethylenimine layer.

9183-91, Session 8

Transient electroluminescence and current responses of organic light-emitting diodes under high current density in microsecond scale

Kou Yoshida, Hajime Nakanotani, Kyushu Univ. (Japan) and ERATO, JST (Japan); Le Zhang, Kyushu Univ. (Japan); Chihaya Adachi, Kyushu Univ. (Japan) and ERATO, JST (Japan)

To realize electrically pumped organic diode lasers, injection of high current density in the device is a crucial issue, and suppression of device breakdown caused by Joule-heating is mandatory. One of the method to suppress the breakdown is operation of devices with short duration time (< ?s), i.e., pulse operation. However, since the effect of Joule-heating under pulse operation still unclear, it is important to understand whether Joule-heating would limit the maximum current density and lower the electroluminescence (EL) efficiency by enhancing non-radiative decay process. In this study, we explored transient characteristics of organic light-emitting diodes (OLEDs) having a p-i-n structure under high current density with application of 5 ?s pulse voltage. As a result, a steep increase of current density within the pulse width and the response was observed and, the response of OLEDs on the different substrates having different thermal conductivity, explained the effect of Joule-heating. In addition, we observed an EL efficiency decrease within the pulse duration. From the results of pump and probing method using double voltage pulse with different intervals, we found the EL efficiency decreasing caused by the Joule-heating are not significant, while other quenching mechanisms such as singlet-triplet annihilation result in the decrease.

9183-38, Session 9

Orbital angular momentum in organic microlasers *(Invited Paper)*

Noel C. Giebink, The Pennsylvania State Univ. (United States)

Helically-phased beams carrying discrete orbital angular momentum (OAM) are being explored for use in applications ranging from optical trapping to high speed communication. These beams are typically generated through conversion of conventional laser modes, however, many applications would benefit from direct semiconductor OAM laser sources. This talk will focus on a new class of evanescently-coupled organic semiconductor microdisk/ring laser with vector vortex beam emission and OAM quanta exceeding 100?. We will explore various OAM superpositions and twisted far-field beam profiles achieved by deformed, compound microring, and coupled microdisk resonators that may serve as a practical route to many OAM-anticipated applications.

9183-39, Session 9

Organic semiconductor lasers for Raman spectroscopy *(Invited Paper)*

Uli Lemmer, Xin Liu, Karlsruher Institut für Technologie (Germany)

Organic semiconductor lasers are particularly interesting for applications as tunable low bandwidth light sources in the visible spectral range. Distributed feedback (DFB) lasers using organic active materials are promising for spectroscopic applications, being enabled by the broad spectral gain, the low laser threshold and the efficient energy conversion in the active material. Additionally, printability and the possible integration into miniaturized systems render these devices very interesting for various sensing applications. These features are very favorable for Raman spectroscopy systems. Recently, we have successfully applied organic semiconductor DFB lasers for Raman spectroscopy via free space excitation and illustrated this approach by measuring Raman spectra of sulfur and cadmium sulfide [1]. Organic analytes can be detected by combining the excitation by an organic semiconductor laser with enhanced signals which are observed using surface enhanced Raman spectroscopy (SERS). We have successfully applied organic semiconductor DFB lasers as excitation sources in surface-enhanced Raman spectroscopy. The performance of a fibre-coupled organic semiconductor DFB laser in SERS measurements was verified using rhodamine 6G (R6G) as analyte. We foresee advantages due to the high tunability of the organic semiconductor lasers. Furthermore, integration of organic lasers into lab-on-a-chip devices could enable miniaturized Raman detection schemes for biomedical analysis.

[1] X. Liu, P. Stefanou, B. Wang, T. Woggon, T. Mappes, and U. Lemmer, “Organic semiconductor distributed feedback (DFB) laser as excitation source in Raman spectroscopy,” Opt. Express 21, 28941 (2013).

9183-40, Session 9

Diode-pumped polymer lasers: photophysics of long pulse operation *(Invited Paper)*

Graham A. Turnbull, Guy L. Whitworth, Yue Wang, Univ. of St. Andrews (United Kingdom); Alexander Kanibolotsky, Peter J. Skabara, Univ. of Strathclyde (United Kingdom); Ifor D. W. Samuel, Univ. of St. Andrews (United Kingdom)

The efficient light emission and simple processing of conjugated polymers make them attractive materials for inexpensive visible lasers. Currently these lasers are optically pumped and operate in a pulsed mode. It would be very attractive to advance the operation of polymer

lasers towards the continuous-wave regime, but the influence of triplet states are understood to limit pulse durations. Recent advances in the use of nitride diode lasers and LEDs to pump polymer lasers present new opportunities to understand better the physics of these lasers in the long-pulse regime. In this paper we explore the operation of an LED-pumped polymer laser under long-pulsed operation, and show how the accumulation of triplet states affects the laser threshold, efficiency and dynamics. We also present a study of long-pulse operation of a polymer laser, when pumped by well-controlled pulses from a nitride laser diode. We explore the build-up and relaxation of the processes that affect laser action, and discuss the influence of excited states and thermal effects.

9183-41, Session 9

Electrospun conjugated polymer nanofibers as miniaturized light sources: control of morphology, optical properties, and assembly *(Invited Paper)*

Andrea Camposeo, Consiglio Nazionale delle Ricerche (Italy) and Istituto Italiano di Tecnologia (Italy); Vito Fasano, Univ. del Salento (Italy) and Istituto Italiano di Tecnologia (Italy); Maria Moffa, Alessandro Polini, Consiglio Nazionale delle Ricerche (Italy); Daniela Di Camillo, Fabrizio Ruggieri, Sandro Santucci, Luca Lozzi, Univ. degli Studi dell'Aquila (Italy); Luana Persano, Consiglio Nazionale delle Ricerche (Italy) and Istituto Italiano di Tecnologia (Italy); Dario Pisignano, Univ. del Salento (Italy) and Consiglio Nazionale delle Ricerche (Italy) and Istituto Italiano di Tecnologia (Italy)

Light-emitting nanostructures made by conjugated polymers show interesting emission and electronic properties. In this work we report on novel approaches for the fabrication and control of light-emitting nanofibers by electrospinning. The shape, size and light-emitting properties of the fibers can be specifically tailored by acting on the composition of the solution used for the electrospinning process, an approach allowing for obtaining fibers ranging from micrometer-sized ribbons to almost cylindrical fibers with diameters down to few hundreds of nanometers. Moreover, following proper process optimization these fibers can also be precisely positioned in ordered arrays by near-field electrospinning, a method that exploits the stable region of the polymer jet. The possibility of precisely shaping the conjugated polymer fibers and of assembling the fiber in ordered arrays, combined with enhanced emission properties, opens interesting perspectives for developing novel emitting flexible nanomaterials suitable for light sourcing and optical sensing.

9183-42, Session 9

Color conversion in polychromatic organic light-emitting field-effect transistors: optical filtering versus reemission *(Invited Paper)*

Heinz von Seggern, Technische Univ. Darmstadt (Germany); Christian Melzer, Univ. Heidelberg (Germany)

The color conversion process of a polychromatic organic light-emitting field-effect transistor is investigated experimentally and compared to an analytical device model. The device of interest consists of a semitransparent top gate bottom contact F8BT-based organic light emitting transistor (OLET) whose channel is partially covered by a wedge shaped color conversion layer out of rubrene. The model is based on the Shockley equations for a bipolar transistor [1] whose light intensity is related to the electron and hole currents recombining in the transistor channel. The absorption and conversion of the so emitted F8BT light by the rubrene layer can be calculated and allows one to link the optoelectronic response of the employed monochromatic OLET to the optical processes occurring in the color conversion layer. The model indicates that the color shift is rather due to partial absorption of the F8BT emission by rubrene than due to a color conversion process by absorption and reemission of the conversion layer as was claimed earlier [2]. In addition, it will be demonstrated that such a device allows for an independent electrical tunability of emission intensity and color coordinate within the color coordinates of F8BT and rubrene establishing a unique feature of the discussed polychromatic OLET.

[1] R. Schmechel, M. Ahles, H. von Seggern, J. Appl. Phys. 98 084511 (2005)

[2] E. J. Feldmeier, C. Melzer, Organic Electronics 12, 1166 (2011)

9183-43, Session 9

Near-infrared electroluminescence from low-voltage ambipolar field-effect transistors *(Invited Paper)*

Jana Zaumseil, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Near-infrared light (800-1800 nm) is of great importance for optical telecommunication (C-band: 1530-1565 nm, O-band: 1260-1360 nm) and deep tissue imaging (second window from 1000 to 1350 nm). In contrast to the visible light range there are currently no efficient solution-processable, organic near-infrared light-emitting devices with selectable emission wavelengths and narrow linewidths. Possible alternatives are devices based on lead sulfide nanocrystals or carbon nanotubes. Semiconducting single-walled carbon nanotubes (s-SWNT) are promising near-infrared emitters as their emission wavelength is determined by their chirality vector (m,n) and they show very narrow emission linewidths. They also emit strongly polarized light. However, emission efficiency and brightness of carbon nanotube-based emitters have been extremely low so far. Here we demonstrate bright near-infrared electroluminescence from low-voltage (<2 V) ambipolar field-effect transistors based on aligned networks of chirality-selected s-SWNT. These networks contain only certain nanotube species, e.g., (6,5), (7,5) or (10,5) nanotubes that were extracted by dispersion with polyfluorene copolymers. The resulting ambipolar transistors exhibit narrow emission zones whose position can be tuned by the applied voltages. Depending on nanotube species polarized emission at 1000 nm, 1050 nm and 1300 nm is obtained with linewidths of less than 50 nm. Quantum efficiency and colour purity of s-SWNT emitters are superior to low-bandgap polymers and other organic near-infrared light-emitting devices.

9183-44, Session 10

Concentration effect on the optical absorption and luminescence properties of disperse red-13 in silica spheres

Kwang-Sun Kang, Kyungil Univ. (Korea, Republic of)

A reversible color change and large absorption band shift have been observed for the disperse red-13 (DR-13) attached on the surface of the monodisperse silica spheres. Two step synthetic processes including urethane bond formation and hydrolysis-condensation reactions were used to attach the DR-13 on the surface of the silica spheres. After the reaction, the characteristic absorption peak at 2270 cm-1 representing the –N=C=O asymmetric stretching vibration disappeared, and a new absorption peak at 1700 cm-1 corresponding the C=O stretching vibration appeared. A visual and reversible color change was observed before and after wetting in alcohol. Although the absorption peak of DR-13 in alcohol is at 510 nm, the absorption peak shifts to 788 nm when it is dried. The absorption peak shifts to 718 nm when it is wetted in alcohol. This result can be explained by the formation of intramolecular charge transfer band.

9183-45, Session 10

High-speed visible light communication using a conjugated polymer color converter *(Invited Paper)*

Ifor D. W. Samuel, Univ. of St. Andrews (United Kingdom); Hyunchae Chun, Univ. of Oxford (United Kingdom); Pavlos Manousiadis, Univ. of St. Andrews (United Kingdom); Sujan Rajbhandari, Univ. of Oxford (United Kingdom); Dimali Amarasinghe, Univ. of St. Andrews (United Kingdom); Grahame E. Faulkner, Univ. of Oxford (United Kingdom); Dobroslav Tsonev, The Univ. of Edinburgh (United Kingdom); Jonathan J. D. McKendry, Martin D. Dawson, Univ. of Strathclyde (United Kingdom); Graham A. Turnbull, Univ. of St. Andrews (United Kingdom); Harald Hass, The Univ. of Edinburgh (United Kingdom); Dominic C. O'Brien, Univ. of Oxford (United Kingdom)

There is growing interest in using visible light for communications (so called "Li-Fi") to overcome the limited radio frequency bandwidth for Wi-Fi. However, the phosphors typically used to make white light from blue Gallium nitride LEDs have long excited state lifetimes that severely limit the bandwidth of data transmission. We show that the short radiative lifetime of conjugated polymers makes them attractive materials to overcome this limitation. The copolymer super-yellow was used in combination with a gallium nitride micro-LED to generate white light. This enabled data transmission at 1.68 Gb/s over a distance of 3 cm, and 840 Mb/s over a distance of 2 m. These are the fastest results so far reported for a single white-source visible light communication system, and present a possible new application area for conjugated polymers.

9183-46, Session 10

Recent advances in stacked inverted top-emitting organic electrophosphorescent diodes *(Invited Paper)*

Bernard Kippelen, Keith A. Knauer, Ehsan M. Najafabadi, Yinhua Zhou, Canek Fuentes-Hernandez, Georgia Institute of Technology (United States)

In this talk, we will discuss recent advances in green and white electrophosphorescent stacked organic light-emitting diodes (OLEDs) with inverted top-emitting structures. These devices combine the advantages of having inverted electrode positions, a top-emissive design, and a stacked architecture. The stacked OLEDs have been optimized by the choice of their constituent materials and the thicknesses of the layers in the connecting-unit. The connecting-unit between the two light-emitting units consists of Al/LiF/HAT-CN. The interface between the HAT-CN and the neighboring hole-transport material of TAPC is believed to lead to efficient free charge carrier generation. The electrical and optical characteristics of the stacked OLEDs are evaluated by comparing their performance to that of the constituent single-unit OLEDs. In the case of the green OLEDs, at a luminance of 1000 cd/m2, a single-unit OLED is shown to have a current efficacy of 46.8 cd/A and a two-unit stacked OLED has a current efficacy of 97.8 cd/A. When an optical outcoupling layer of ?-NPD is added to the stacked OLED, a current efficacy exceeding 200 cd/A at a luminance value of up to 1,000 cd/m2 is achieved. The white OLEDs are made by stacking blue and orange light-emitting units. At a luminance of 1000 cd/m2, single-unit blue OLED and orange OLED yield current efficacies of 28.4 cd/A and 16.3 cd/A, respectively. The stacked white OLED is shown to have a current efficacy of 18.5 cd/A at 1000 cd/m2. Finally, we will also demonstrate OLEDs that are fabricated on cellulose nanocrystal substrates and discuss how the use and integration of such naturally-derived materials can reduce the environmental footprint of organic electronic devices such as OLEDs.

9183-47, Session 10

Pseudo natural lights for lighting based on high band-number organic light-emitting diodes and light-emitting diodes

Jwo-Huei Jou, Kun-Yi Chou, Ching-Heng Hsieh, Fu-Chin Yang, National Tsing Hua Univ. (Taiwan)

Natural lights, like the sunlight on earth, are most welcome for lighting due to their relatively smooth and continuous spectrum over the entire visible range. It is highly desirable if artificial lighting sources can be made with high natural light spectrum resemblance. We will demonstrate the design and fabrication approaches for pseudo natural lights for lighting with very-high color rendering index (CRI > 90) and very high natural-light spectrum resemblance based on high band-number organic light-emitting diodes (OLEDs) as well as light-emitting diodes (LEDs). By employing 6 blackbody radiation complementary organic emitters, for example, pseudo natural lights with dawn light-, sunny daylight-, and dusk-hue-style emissions are obtainable with a CRI greater than 90, and a natural light spectrum resemblance greater than 92. For the LED counterparts, a much high band-number would be required to achieve the same due to their intrinsic narrow-band emission. However, by coupling with one or two broad-band phosphors, high quality pseudo natural lights can still be obtained.

9183-48, Session 11

Brighter, better, whiter, more: recent advances in white-emitting OLEDs *(Invited Paper)*

Malte C. Gather, Univ. of St. Andrews (United Kingdom) and Technische Univ. Dresden (Germany)

Our recent work on organic light-emitting diodes will be discussed, with particular focus on the generation of white light. We report on novel strategies for improved color quality and efficiency in top-emitting OLEDs and on their optical modeling. These devices comprise ultra-thin metal layers with excellent optical transmission across the visible spectrum, on par with the notoriously difficult to handle ITO. Time permitting, we also cover random and periodic scattering structures for extraction of light guided within the organic layers of OLEDs. Finally, we describe a potentially highly attractive scheme for driving white OLEDs with alternating current signals.

9183-49, Session 11

High efficiency hybrid white OLEDs *(Invited Paper)*

Dongge Ma, Changchun Institute of Applied Chemistry (China)

White organic light-emitting diodes (WOLEDs) are attracting significant attention due to its unique merits of fabrication of large-scale for solid-state lighting sources, full-color displays and backlights for liquid-crystal displays [1]. The phosphorescent WOLEDs showed outstanding efficiency since all electrically generated singlet and triplet excitons can be harvested by phosphorescent emitters [2]. However, the development of phosphorescent WOLEDs is severely limited by the absence of efficient deep-blue phosphorescent emitters with an operational lifetime suitable for commercial applications [3]. Hybrid WOLEDs which combine a stable blue fluorophor with red and green (or yellow) phosphors have been reported to show much more stable operation with respect to all-phosphorescent WOLEDs by avoiding the relatively unstable blue phosphor, but not affect the harvesting of both triplet and singlet excitons for efficient white emission [4]. Thus, hybrid WOLEDs with three primary colors are more in line with the requirements of lighting application.

Here, we fabricated high efficiency hybrid white OLED based on a yellow

phosphorescent dopant doped a blue fluorescent host as the emissive layer. The devices emitted good white light, where the yellow light is from the phosphorescent dopant and the blue light is from the fluorescent host. It can be seen that the fabricated hybrid white OLEDs also showed high efficiency. The maximum power efficiency reached 121.9 lm/W, and kept 74.1 lm/W at 1000 cd/m2. The further investigation demonstrates that not only the used host, but also the electron- and hole-transporting layer materials have great effect on the device efficiency. We give detailed discussion..

9183-50, Session 11

High performance hybrid white OLEDs based on new platinum complexes and new blue fluorescence host *(Invited Paper)*

Chin-Ti Chen, Academia Sinica (Taiwan)

A new series of heteroleptic platinum complexes containing 4-hydroxy-1,5-naphthyridine derivative with different substituents such as methyl, dimethyl, phenoxy, piperidine or carbazole unit as the first ligand and 2-(2,4-difluorophenyl)pyridine as the second ligand were synthesized and characterized. The crystal structure of platinum complex with phenoxy substitution was determined by the single-crystal X-ray diffraction crystallography. The crystal structure showed trans-coordinated between N atoms of 4-hydroxy-1,5-naphthyridine and 2-(2,4-difluorophenyl) pyridine ligand in distorted square-planar geometry. Their photophysical properties and electrochemical properties were examined. All platinum complexes in these series exhibited dual emissions in solution with components assigned to monomers and aggregates in the region of 545-593 nm. By introducing bulky substituent carbazole unit, platinum complex displayed less aggregation tendency due to its steric hindrance. For application, organic lighting diodes (OLEDs) were fabricated by vacuum thermal evaporation process using these platinum complexes as the phosphorescent dopant. Two types of host materials, conventional CBP or 4P-NPD, were employed in the device configurations.
With the conventional CBP host, greenish-yellow or orange-red electroluminescence (EL) was obtained, depending on the substituents of platinum complexes. Upon doped phosphorescent emitters to 4P-NPD host, multicolor of platinum emitters from greenish-yellow to orange-red were achieved with varied doping concentration. High color rendering index hybrid white OLEDs (CRI > 80) were also obtained from a single dopant with an appropriate dopant concentration of platinum emitters together with blue fluorophore 4P-NPD, considering as a simple device configuration. Moreover, double emissive layer devices were fabricated to further improve device efficiencies.

9183-51, Session 11

High performance white OLED with organic and inorganic nanostructure for display application *(Invited Paper)*

Nam Sung Cho, Joohyun Hwang, Doo-Hee Cho, Seung Koo Park, Jonghee Lee, Jaehyun Moon, Jin-Wook Shin, Chul Woong Joo, Hye Yong Chu, Jeong-Ik Lee, Electronics and Telecommunications Research Institute (Korea, Republic of)

In recent years, significant advances of Organic light-emitting diodes (OLEDs) have been made in the active-matrix OLED displays, and OLED has been one of the biggest market leaders in mobile. Furthermore, OLED is expanding its application to large-size display not only ultra thin 55-inches but also and curved 55-inches OLED TV in market. In OLED display technologies, white OLEDs (WOLEDs), which generate white or broadband light of visible spectra, are devices at the center of attention not only for lighting applications but also for large-sized OLED displays. Among WOLEDs, WOLEDs embedded by RGB color filters are an alternative due to cost and technology issues associated with a regular RGB scheme currently used in mobiles. For this reason, research efforts on WOLEDs are strongly desired in display areas, for a significant market potential.

In this talk, we report firstly the design principle and fabrication of 2-layered tandem white device with optimal charge generation layers (CGL); p- and n-type layer and secondly how to maximize the efficiency of white device which we combine the white OLED and light extraction. After that optimization of white device, we apply organic and inorganic nanostructure that act light extraction layers, which enhance the efficiencies of WOLED. The former is a solution-processed wrinkled structure based film which was applied on the outer glass substrate and the latter is random SiOx nanostructure, which formed between the substrate and anode. In white OLED optimization, we achieved very high efficiency, 31 lm/W at 4,400 nit, that is one of the highest efficiency in white OLEDS. To examine the light extraction ability, we will fabricate OLEDs with the wrinkled structure as an external light extraction layer or internal random SiOx nanostructure.

We believe that those simple, inexpensive, and reliable light extraction structure can be a key technology and will greatly contribute the development of white OLEDs for display applications.

9183-52, Session 12

Light management in flexible OLEDs *(Invited Paper)*

Stephan Harkema, Holst Ctr. (Netherlands)

In collaboration with our industrial and academic partners, Holst Centre aims to develop generic technologies for large area flexible OLED lighting architectures, including thin film water barriers, which can be processed with roll-to-roll (R2R) compatible technology with high yield. This presentation will give an overview of our technological developments in flexible OLEDs with high light extraction. Highlights from our work will be presented, including devices on plastic and metal foil substrates with state-of-the-art thin film flexible barrier performance (black spot free flexible OLEDs after more than 2000 hours in 60 degrees C/90%RH accelerated lifetime conditions). We will demonstrate modeling and application of state-of-the-art light extraction techniques in flexible devices in order to exceed doubling of the performance of standard glass-based OLED devices.

9183-53, Session 12

Highly efficient organic light emitting diodes fabricated on corrugated high refractive index substrates

Wooram Youn, Jinhyung Lee, Minfei Xu, Chaoyu Xiang, Rajiv K. Singh, Franky So, Univ. of Florida (United States)

Due to the refractive index mismatching between layers in organic light emitting diodes (OLEDs), the external quantum efficiency (EQE) is typically about 20-25%. In order to overcome this limitation, high-refractive-index substrates were used to remove the waveguide mode. However, the efficiency is still limited by of the loss of surface plasmon (SP) mode at the interface between the organic and metal layers. While it is relatively easy to extract the substrate modes, the grand challenge in OLEDs is how to extract the surface plasma modes. In this work, we demonstrate that a Bragg diffraction grating structure with a broad distribution of periodicity can be exploited to extract the SP mode, resulting in an EQE exceeding 60%.

Phosphorescent tris(2-phenylpyridine) iridium [Ir(ppy)3]-based OLEDs were fabricated on corrugated sapphire substrates with periodicities between 0.3 and 0.5 um. Using a macrolens to extract the substrate mode, an EQE up to 60.8% was achieved. Because of the "defects" present in the gratings, the resulting electroluminescence is unchanged with an emission profile very close to a Lambertian emitter. From the emission characteristics of the OLEDs fabricated on these corrugated structures, we conclude that the use of corrugated structures on high-refractive-index substrates is very effective to extract the SP modes.

9183-54, Session 12

Light manipulation in organic light-emitting devices by integrating micro/nano patterns

Jing Feng, Qi-Dai Chen, Hong-Bo Wang, Yi Zhao, Hong-Bo Sun, Jilin Univ. (China)

Microstructure with wavelength to subwavelength-scale periodicity has played an important role in optical and optoelectronic devices, particularly in optical fibers, distributed feedback lasers, LEDs and solar cells etc. through manipulating the generation and propagation of photons in materials. This talk will introduce our systematic investigations on the fabrication of micro/nano structure in organic optoelectronic devices and their effects on improving the device performance. The waveguide and surface plasmon-polariton (SPP) modes that were generally lost in conventional bottom-emitting organic light-emitting devices (OLEDs) have been successfully recovered by employing a microstructure, and a much enhanced light extraction has been observed. We demonstrate that the introduction of a periodic corrugation into the top-emitting OLEDs is effective in relieving the tradeoff between device lifetime and efficiency, through the coupling of the SPPs associated with the Ag cathode and the microcavity modes. Moreover, the viewing characteristics of top-emitting OLEDs have been improved by employing microstructure to construct a microcavity with periodically changed cavity length. Microstructure has been employed in organic laser and organic solar cells to lower the lasing threshold and improve the light absorption, respectively.

9183-55, Session 12

High index polymer substrates with built-in scattering properties for low cost, flexible OLEDs with improved efficiency

Eunhye Kim, Seunghyup Yoo, Hyunsu Cho, Jin Chung, Jaeho Lee, Eungjun Kim, KAIST (Korea, Republic of)

Improving light extraction efficiency of organic light-emitting diodes (OLEDs) is a key agenda to do for bringing the commercialization of OLEDs closer. In that respect, use of a high refractive index substrate has been known to be highly effective in suppressing waveguide modes and thereby opening up a way to enhance the outcoupling efficiency provided that an external substrate structuring is accompanied to extract substrate confinement modes. However, use of a specialty glass and lack of high-index micro lens arrays have been regarded as a bottleneck in exploiting the full benefits this high-index substrate scheme can offer. Difficulty in applying this technique to flexible OLEDs has also been a concern.

In this work, high refractive index polymer substrates with inherent scattering properties are explored as a simple platform for light extraction enhancement in flexible organic light-emitting diodes (OLEDs). Being tested in highly efficient green phosphorescent OLEDs (PHOLEDs), the proposed scheme leads to an enhancement of external quantum efficiency (EQE) and power efficiency (PE) by approximately 30~50%, yielding the max efficiency close to 30% and 100 lm/W in flexible green PHOLEDs. The observed phenomena are then quantitatively analyzed based on a trans-scale optical model that couples an advanced wave-optic analysis based on a power dissipation model[1] and a geometrical-and statistical-optic analysis considering the scattering properties.

[1] Mauro Furno, Rico Meerheim, Simone Hofmann, Bjoern Luessem, and Karl Leo, Phys. Rev. B 85, 115205 (2012).

9183-56, Session 12

Light extraction from solution processed organic light emitting diodes

Srinivas P. Sista, Xiaolei Shi, Jie Liu, Kevin H. Janora, GE Global Research (United States)

In a typical organic light emitting diode (OLED) nearly 80% of the light generated in the emissive layer remains trapped either inside the substrate or inside the organic layers or is lost to the cathode. Here we demonstrate 50% EQE entitlement from solution processed white OLEDs using a high index substrate (Refractive Index (RI) = 1.78) to extract the organic modes and a high index hemisphere (RI = 2.0) to extract the substrate modes to the air. This shows that there is plenty of room to improve the efficiency of white OLEDs using existing material set and the increased efficiency also results in improvement in lifetime.

Several different approaches are being explored in efficiently extracting the substrate and device modes to air. Though several practicable external light extraction approaches are available, cost effective and manufacturable internal light extraction approaches are still a challenge. Internal light extraction approaches include modifying the interface between ITO & glass such as corrugated substrates, 2-dimensional photonic crystal structure, low index grids and volumetric scattering layers. Most of the substrate modification techniques lead to non-uniformities in the substrate that make characterization of light extraction films by fabricating OLEDs a challenging and time consuming task. Here we apply a novel prism coupling method (PCM), a simple and elegant tool to characterize outcoupling films. We show the effectiveness of PCM in estimating the light extraction efficiency of outcoupling films and can expedite the selection and optimization of various light extraction approaches without the need to build OLEDs. Also other challenges in extraction light from solution processed OLEDs are presented.

9183-57, Session PWed

Organic light-emitting devices based on organic single crystals by improved contact between the metallic electrodes and the crystal

Ran Ding, Yu-Kun Wu, Ping-Rui Yan, Hong-Bo Wang, Yi Zhao, Qi-Dai Chen, Jing Feng, Hong-Bo Sun, Jilin Univ. (China)

Organic single crystals have attracted their extended interests as active layer material in application of optoelectronic and electronic devices. Their high order molecular packing, high chemical purity and high carrier mobility are the main motivation for research on the organic single crystals such as optically pumped lasers,[1] organic field-effect transistors,[2] and organic light-emitting diodes (OLEDs). Organic single crystals using for electroluminescent devices are currently being studied and opened up a new application in single crystals since Pope et al.[3] However, the amount of reports on OLEDs based on organic single crystals is scarce. A significant problem is the contact problem which caused by the lamination between bottom electrode and crystal through the weak van der Waals force to achieve uniform surface emission from the OLEDs. Thus, there is a pressing need a simple, non-destructive and mechanically flexible method to resolve the contact problem to make high throughput in device fabrication of single crystals.

In this work, a simple and non-destructive method template stripping, has been applied into the single crystal based OLEDs with a series material of 2,5-bis(4-biphenyl)bithiophene (BP2T) and 1,4-bis(4-methylstyryl)benzene (BSB-Me) to improve the contact problem (see figure 1). On the basis of this technique, single-crystal-based OLEDs with better contact between the crystals and electrodes are expectable.[4] Both anodes and electrodes of the crystal OLEDs can be deposited onto the opposite surface of the organic single crystals by thermal evaporation on both sides, so that a much improved contact between the crystals and the electrodes can be realized, which enhance the carrier injection into the active layer of organic single crystals with bright electroluminescence (see figure 2).

9183-58, Session PWed

Broadband light extraction from white organic light-emitting devices by employing corrugated metallic electrodes with dual periodicity

Yan-Gang Bi, Yu-Kun Wu, Ping-Rui Yan, Hong-Bo Wang, Yi Zhao, Qi-Dai Chen, Jing Feng, Hong-Bo Sun, Jilin Univ. (China)

White organic light-emitting devices (WOLEDs) are of interest on the ground of their potential applications for full-color flat-panel display and solid-state lighting. High efficiency is one of key issues for its commercial applications, while, majority of photons produced by exciton decay are trapped inside of OLEDs in forms of waveguide (WG) modes in organic/indium-tin-oxide (ITO) anode layers and surface plasmon–polariton (SPP) modes associated with the metallic electrode/organic interface. Broadband extraction is important for the efficient outcoupling of the trapped photons, especially for that trapped in the WOLEDs whose spectra covering the whole visible wavelength. OLEDs with two metallic electrodes by employing metallic film with high optical transmission and electrical conductivity to replace ITO as anode could eliminate the power lost to the WG modes in ITO. Wavelength-scale periodic microstructures introduced into the OLEDs are suitable for specific narrow range of wavelength to couple the trapped SPP modes? and applicable only for monochromatic OLEDs.

In this communication, broadband excitation and outcoupling of the SPP modes in the WOLEDs has been realized by introducing a two-dimensional (2-D) grating with dual-periodic corrugation into the WOLEDs (Figure 1). The 2-D grating consisted two sets of corrugations with different periods can broaden the SPP resonance compared to that of the monoperiodic grating. The blue and orange emission are both efficiently extracted from the WOLEDs based on the two complementary color strategies by adjusting appropriate periods of the dual-periodic corrugation. A 37% enhancement in the current efficiency compared to those of the conventional planar devices has been obtained (Figure 2).

9183-60, Session PWed

The application of high efficient yellow phosphorescent material to white OLEDs

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A new type of thiopyridinyl-based iridium molecule (POT) was used as the yellow phosphorescent material in our research. On fabricating a yellow PHOLED by doping POT with host as the emitter, the device achieved a high power efficiency of 66.0 lm/W and an external quantum efficiency (EQE) of 23.2%. On the other hand, A white organic light-emitting diode(WOLED) with a high power efficiency has been demonstrated by dispersing a host-free, yellow phosphorescent material in between double blue phosphorescent emitters. In this study, we introduce a simple process for generating yellow emission of a WOLED by using the B/Y/B EML configuration. The B/Y/B EML configuration can achieve a higher efficiency and a smaller color shift with various operational brightness values. Based on this device concept as well as the molecular engineering of the blue phosphorescent host material and light-extraction film, a WOLED with a power efficiency of 95 lm/W at a practical brightness of 1000 cd/m2 with CIE coordinates (CIEx, y) of (0.36, 0.48) can be achieved.

9183-61, Session PWed

The profiling of planar illuminative patterns using multiple white organic light-emitting diodes

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The feasibility of applying multiple white organic light-emitting diodes (WOLED) to establish specific planar illuminative patterns for general lighting without secondary optical components was experimentally investigated in smaller scale by using a single-axis automatic optical measuring system. The white organic light-emitting diode (WOLED) is one of the upcoming lighting sources. Its planar device structure can generate planar lighting source without using secondary optical components. The planar illuminative patterns created by any lighting source are crucial for practical purpose. The ideal illuminative pattern for smaller-scale lighting such as desk lamp is expected to be uniform on relatively large planar area. A practical lighting source should associate with adjustable characteristics to generate various illuminative pattern for applications. Regular white LED's (WLED) have been used in lighting applications for years. Its point-source optical distribution features has been theoretically and experimentally investigated widely. The various planar illuminative patterns of WLED's can be achieved by applying specific secondary optical components or combing multiple WLED's. However, the issues of applying WOLED as adjustable lighting source for specific illuminative patterns have rarely been discussed in the past. The lighting source in our experiment consists of three WOLED mounted side-by-side with changeable tilting angle. This adjustable lighting source with three planar WOLED may be feasible for forming required illuminative pattern without using secondary optical components. Our preliminary experimental result measured from a 3-WOLED source with specific tilting angle in smaller scale suggests that a relatively uniform illuminative area can be established in practical mean without secondary optical components.

9183-62, Session PWed

Two-color emission in three-layer heterostructure OLETs

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Three-layer heterostructure organic light emitting transistors, OLETs, were fabricated on the basis of device configuration described in Nat. Mater. 9, 496, 2010 with varied parameters of the deposited layers. These changes resulted in observation of two-color switchable emission instead of single-color emission described in the article.

The OLETs (ITO/PMMA/DH-4T/Alq3:DCM/DFH-4T/LiF/Al) were fabricated on indium tin oxide coated glass substrates. The dielectric layer was spin coated from poly(methyl methacrylate) (PMMA) solution in ethyl lactate. The light emitting layer (tris(8-hydroxyquinolinato)aluminium:4-(dicyanomethylene)-2-methyl-6-(p-dimethylaminostyryl)-4H-pyran, DCM:Alq3) was sandwiched between the hole transport (?,?-dihexyl-quaterthiophene, DH-4T) and the electron transport (?,?-diperfluorohexyl-quaterthiophene, DFH-4T) layers evaporated at the rate <6Å/min (~3Å/min). The thicknesses of these layers were 21nm, 40nm and 25nm, respectively.

The ambipolar (V-shaped) transfer curves were recorded from the manufactured devices. Two-color emission (red and green) was observed during the transfer curve acquisition. The red emission was observed to take place at the bias conditions allowing the hole transport. Accordingly, the green emission was caused by the electron current. The red emission is originated from the Alq3:DCM layer that was proved by comparison of the measured spectrum of the OLET to the spectrum of corresponding single-layer Alq3:DCM OLED. We suggest that the green emission is originated from the electron transport layer. To prove that, the OLETs without electron transport layer were fabricated. No green emission was noticed in this case while the red emission is maintained. Moreover, the single-layer OLED and OLET fabricated from DFH-4T expressed the green color emission similar to that of tree-layer heterostructure OLET.

9183-63, Session PWed

Recent progress in pixel patterning techniques for high resolution OLED displays

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We report progress in development of pixel patterning techniques for achieving high resolution OLED displays. While OLED displays are expected as next generation displays, achieving high resolution over 300ppi with high aperture ratio is still challenging since the conventional vacuum deposition patterning technique utilizing fine metal shadow masks has a limitation in alignment accuracy. This problem is mainly due to deformation of these thin masks (t~30um) which occurs upon stretching the masks on mask holders for mounting and alignment with TFT backplane substrates. Recently, we proposed a pixel patterning technique that uses polyimide sheets patterned by laser ablation as an alternative shadow mask technique. The issue of the mask deformation due to straining can be avoided by this technique since the dry laser ablation patterning allows us to pattern the polyimide sheets after they are strained by the mask holder. Furthermore, it is even possible to pattern the polyimide sheet by laser ablation in-situ on the TFT backplane substrates after applying the sheet on the substrate. Since slits on the masks are created over the desired TFT locations in this technique, the mechanical mask alignment step can be eliminated, hence more accurate pixel patterning is possible. In this work we will present recent progress on the development of this technique, including the successful demonstration of RGB pixel patterning of OLEDs with small feature sizes (~25um) and high aperture ratio (~100%). In addition, alternative techniques for achieving high resolution pixel patterning will also be discussed.

9183-64, Session PWed

All-solution processed transparent organic light emitting diodes with graphene as top cathodes

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Graphene is a flexible two-dimensional sheet of sp2-hybridized carbon atoms that have a strong potential to be transparent electrodes in organic electronic devices with excellent conductivity and highly transparent properties. Despite its strong potential as a transparent conductor, the work function of pristine graphene causes an unfavorable carrier injection because of the high injection barrier at interface between graphene electrodes and contacted organic layers. Recently, it was successfully demonstrated that organic light emitting diodes (OLEDs) can achieve high luminous efficiencies with p-doped graphene anodes. However, there still lacks of reliable methods to fabricate an n-doped graphene cathode. In this study, the transfer of graphene with new polymer-free method is demonstrated to obtain OLEDs with truly all-solution processes, including top electrodes. This polymer-free transfer method provides an efficient way to modify the work function and sheet resistance of graphene to be used as electrodes for organic devices. Not only p-type graphene for anodes, n-type graphene for cathode can also be obtained with this method. With n-doped graphene layers used as top cathodes, all-solution processed transparent multilayered OLEDs were demonstrated without any vacuum processes. The results show that graphene electrodes can be used in a wide variety of organic optoelectronics with more efficient doping and simple transfer techniques.

9183-65, Session PWed

Exciton-polaron-induced aggregation of wide-bandgap organic semiconductors and its primary role in the degradation of phosphorescent organic light-emitting devices

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Despite their unique ability to realize a device internal quantum efficiency of nearly 100%, phosphorescent organic light-emitting devices (PhOLEDs) generally have shorter lifetimes when compared with their fluorescent counterparts. Understanding their degradation behavior is therefore essential for developing long-lived devices. To this end, we investigate the degradation mechanisms of PhOLEDs.

Contrary to expectations, we recently found that PhOLEDs degradation is not closely related to guest molecules where photons are emitted, but primarily originates from the aggregation of host molecules. We have determined that the aggregation of host molecules arises from exciton-polaron interactions triggered by the co-existence of both excitons and polarons on host molecules when under electrical driving. This exciton-polaron-induced aggregation (EPIA) occurs to host materials (HMs) only in the vicinity of HM/electron transport material interfaces, where most excitons and polarons accumulate. The EPIA process is associated with the emergence of new emission bands at longer wavelengths in the electroluminescence spectra of HMs which can be detected after prolonged device operation. Such EPIA phenomenon is found in a variety of wide-bandgap materials commonly used as hosts in PhOLEDs. Quite notably, the extent of EPIA appears to correlate with the materials bandgap rather than with their glass-transition temperatures. Since the use of wide-bandgap materials as hosts is a prerequisite for achieving high efficiency in PhOLEDs, these findings uncover a predominant mechanism that is essentially responsible for the low stability of PhOLEDs, and elucidate why PhOLEDs are far less stable than their fluorescent counterparts which do not usually use wide-bandgap materials.

9183-66, Session PWed

Exciton-induced degradation in simplified phosphorescent organic light-emitting devices

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Simplified Phosphorescent Organic Light-Emitting Devices (PHOLEDs) that utilize one material, typically 4,4'-bis(carbazol-9-yl)biphenyl (CBP), for both the hole transport layer and the host have attracted much interest due to their improved efficiencies, especially at high luminance. However, studies have shown that their lifetime is shorter than that of the traditional PHOLEDs. In this work, we show that exciton-induced degradation at both the ITO/CBP and CBP/2,2',2"-(1,3,5-benzinetriyl)-tris(1-phenyl-1-H-benzimidazole) (TPBi) interfaces limit device lifetime. In the first case, the formation of excitons near the ITO/CBP interface is found to be due to recombination of holes injected from the ITO anode and electrons leaked from the emission layer (EML). By placing a thin layer of 2,6-bis[3-(carbazol-9-yl)phenyl] pyridine (26DCzPPy), which has a shallower LUMO level than that of CBP and thus prevents electron leakage, and at the same time a similar HOMO level to that of CBP and thus ensures that hole transport is not hindered, at the interface, we show that the lifetime of the simplified PHOLEDs can be extended by one order of magnitude without lowering the device efficiency. In the second case, exciton formed at the CBP/TPBi interface interacts with the polarons nearby, resulting in efficiency loss. By reducing the exciton density at the CBP/TPBi interface by means of increasing the EML thickness, hence widening the recombination zone, the device lifetime can be increased by a factor of 3. Finally, results from the interplay between exciton-induced degradation and ambient degradation in simplified PHOLEDs will be presented.

9183-67, Session PWed

Stability of transition metal oxide doped organic semiconductors

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Electrical doping in organic semiconductors is an important technique to reduce the driving voltage and improve the power efficiency of organic electronic devices. Electrical doping in charge transporting layers in the organic light emitting diodes (OLED), organic photovoltaic cells (OPV) can reduce the contact resistance between electrodes and organic materials. Based on these recent results, highly efficient tandem structured OLED and OPV have been realized using p-doped/intrinsic/n-doped (p-i-n) structures. Various metal oxides such as molybdenum oxide (MoO3), tungsten oxide, vanadium oxide and rhenium oxide (ReO3) along with organic dopants including tetrafluorotetracyanoquinodimethane (F4-TCNQ) and molybdenum tris-[1,2-bis(trifluoromethyl)ethane-1,2-dithiolene] have been widely investigated as p-type dopants. However, the nanocluster formation and the diffusion problems of various dopants such as p-dopants (MoO3 and ReO3) and n-dopants (lithium and cesium) have been referred as the reason of instability of organic electronics having doped organic semiconductor layers. In this presentation, we demonstrate the stability characteristics of transition metal oxide doped organic semiconductors. Molybdenum oxide (MoO3) and 1,4-bis[N-(1-naphthyl)-N'-phenylamino]-4,4'-diamine (NPB) is used for a p-type dopant and a host of simple structured organic devices consisting of ITO/doped/undoped/Al or ITO/undoped/doped/Al. Current density-voltage (J-V) characteristics and capacitance-frequency (C-F) characteristics of hole only device reveal that the sequence of deposited layer affect the stability of organic devices having a doped organic layer and an interface between doped and undoped organic layer. Temperature-dependent conductance/frequency-frequency (G/F-F) analysis also shows that the doping efficiency of MoO3 doped NPB was diminished after the annealing process of doped devices.

9183-68, Session PWed

Development of donor-acceptor-donor type TADF molecules for highly efficient OLEDs

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Recently, we have reported that highly efficient OLEDs using thermally activated delayed fluorescence (TADF) materials comparable to phosphorescent OLEDs. In TADF processes, triplet excitons are converted into emissive singlet excitons via thermal activation. Thus, minimizing the energy gap between the S1 and T1 states is necessary to induce efficient up-conversion from triplet to singlet excited states. The energy gap can be decreased by spatially separating the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) of a molecule. The transition dipole moment between the S1 and S0 states, however, decreases with decreasing the overlap. Therefore, the molecular design for TADF emitters would be different from the traditional molecular design to obtain efficient emitters.

In this paper, we report TADF compounds containing phenoxazine donor and benzazole-based accepter moieties. TADF molecules with donor-accepter-donor (D-A-D) type structure showed higher EL efficiency than donor-accepter (D-A) type ones because TADF molecules with D-A-D type have larger oscillator strength with a small energy gap between singlet and triplet excited states, compared to TADF molecules with D-A type. This finding is useful to develope TADF compounds with high luminescence efficiency. Using one of the D-A-D type compounds, we obtained an OLED with external quantum efficiency of 17.6±1.0 %.

9183-69, Session PWed

Achieving efficient transparent organic light-emitting diodes: the effect of phase changes associated with a capping layer design

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Transparent display is a promising device that can be used as an information hub in the future ubiquitous society. From the efficiency perspectives, TrOLEDs are a challenging device platform because most of the outcoupling structures cannot be adopted for aesthetic reasons. We here present our strategy on improving the efficiency of TrOLEDs without using outcouplig structure and with little compromise in transmittance. In this work, TrOLEDs based on top thin-metal transparent electrodes are adopted because deposition of thin metal films can be done by thermal evaporation in such a way that underlying organic layers are not damaged. Due to the limited transmittance of thin metal films, it is critical to secure a way to control the transmittance of thin metal films in such TrOLEDs; in that respect, a dielectric capping layer on top of a thin metal has been proven useful in controlling the transmittance of the top electrode and thus overall device transparency and performance. Many studies reported up to date, however, have been concentrating only on the thickness optimization of dielectric capping layers. Here, we optimize the location of emission zone by carefully monitoring the change in optical phases upon reflection from a top electrode, which turns out to be significant according to the variation of a capping layer design. With the proposed rational design, efficiency enhancement by as large as 20% is demonstrated in these TrOLEDs without any significant transmittance losses.

9183-70, Session PWed

Blue phosphorescent emitters with high quantum efficiency

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Heteroleptic Ir(III) compound with deep-blue phosphorescence has been synthesized. This molecule has the formula of Ir(dfppy)2(C^N), where C^N= 1-(pyridin-2-yl)-benzoimidazole. We observed unexpected thermally-induced isomerization in 290 'c. It could be not converted the isomer by UV or bellow 250 'c temperature. Molecular structures of isomers are established by MAIDI, X-ray and NMR. Isomers display highly efficient blue phosphorescence in the range of 453-480 and 449-476 nm, at room temperature in solution and in PMMA thin film, with quantum yield of 0.76 and 0.57, respectively. We are going to present the evaluation of EL devices, comparable to the devices using the well-known blue iridium complex, Fir6.

9183-71, Session PWed

Surface plasmon polariton modification in top-emitting organic light-emitting diodes for enhanced light outcoupling

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We report on monochrome top-emitting organic light emitting diodes

(OLEDs) incorporating a hole transport layer (HTL) material with a refractive index lower than the emitter material. Hence the dispersion relation of the surface plasmon polariton (SPP) mode from the opaque bottom metal contact is shifted to smaller in-plane wavenumbers, compared to the absolute value of the wavenumber within the organic emitter.

This is realized experimentally by using Poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) as HTL spin coated onto an opaque aluminum bottom contact. The remaining layers of the top-emitting OLED are deposited by thermal evaporation under UHV conditions. The HTL of the reference sample consists of 2,2',7,7'-tetra(N,N-ditolyl)amino-9,9-spiro-bifluorene (Spiro-TTB) doped with 2,2 -(perfluoro-naphthalene-2,6-diylidene)dimalononitrile (F6-TCNNQ). Optical simulations reveal a shift of the SPP mode from Δk_x = k_{x, PEDOT} ? k_{x, ref.} = ?1.13 ?m^{?1} @ 2.0 eV to Δk_x = ?2.15 ?m^{?1} @ 2.5 eV, efficiently decreasing the area in reciprocal space where energy is dissipated from the emitting dipoles and thus increasing the outcoupling efficiency, as the optical thickness of the complete device is held constant.

Due to the large shift of the dispersion relation, the excited modes are no longer evanescent within the organic material (k_{x, PEDOT} < k = k_0 n_active) and outcoupling of these modes into air becomes feasible, e.g. with attached lens.

9183-72, Session PWed

Characterization, synthesis of solution processable a red phosphorescent iridium(III) complex

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A red phosphorescent Iridium complexes, Ir(TMP-TH)2(acac) Ir(DMA-DT)2(acac) were synthesized for organic light-emitting diodes (OLEDs). This material was designed by result of Gaussian modeling program. The ligand, TMP-TH, have the electron donor and acceptor in structure. Also, hexyl group was added for solubilization condition. So, It showed Intramolecular Charge Transfer(ICT) property. The TMP-TH was synthesized by Suzuki coupling reaction, and Ir(TMP-TH)2(acac) was synthesized by Nonoyama reaction. The UV-Visible absorption peak of TMP-TH was measured to be at 363 nm and its photoluminescence (PL) emission spectrum showed blue light-emission peaked at 425 nm in chloroform solvent. The devices fabricated by Ir(TMP-TH)2(acac) as emitting layer dopant. The device structures were ITO / NPB / CBP: Ir(TMP-TH)2(acac) / Bphen / Liq / Al.

9183-73, Session PWed

Position isomerism as a means to increase the triplet energy in organic host materials for blue phosphorescence

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One of the challenging issues in the design of host materials for efficient organic blue phosphorescence is to raise the triplet (T1) energy high enough to accommodate the already large triplet energy of the blue phosphor. The fundamental difficulty lies in the large exchange energy in organic molecules; this translates into requiring to open up the transport gap by at least 1 eV, placing either the conduction band edge too high or the valence band edge too low, both of which can create their own problems such as high injection barriers and poor air stability. The most successful design strategy so far is via coupling of electron donor and acceptor moieties to form a bipolar molecule. Here we explore the use of position isomerism as a means to control the T1 energy without sacrificing transport properties. By using density functional theory calculations, we take polyfluorene, a common blue fluorescent polymer, and examine how changing the ring positions at which to link individual monomeric units affects photophysical properties. We show that switching the linkage position from para to ortho can increase the T1 energy by 0.36 eV while keeping the rise of the transport gap small. Importantly, the ortho linkage pushes the T1 higher than the meta linkage while keeping the transport gap lower, the latter being critical for injection of charge carriers. The high T1 energy obtains without impacting the spatial distribution of electron density at the transport levels, an important attribute for the safeguarding of charge transport.

9183-74, Session PWed

Characterization of delay fluorescence in Rhodamine 6G and ATTO-532

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In this paper we investigate delayed fluorescence (DF) phenomena in the widely used laser dyes, Rhodamine 6G and its derivative ATTO-532 as a function of excitation energy using highly sensitive time-resolved gated nanosecond spectroscopy. Excitation with UV laser radiation results in delayed emission which arises from singlet states created from geminate pair recombination. For the first time the origins and photo-physical properties of delayed fluorescence in these highly fluorescent molecules is reported.

9183-75, Session PWed

Enhancing light extraction in flexible OLEDs using micro lens arrays and scattering layers

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One of the major advantages of OLEDs is that they can be fabricated on flexible substrates such as polyethylene terephthalate (PET)]. The widely used anode material indium tin oxide (ITO) is brittle and difficult/expensive to fabricate on PET. In this report we investigate the optical losses in flexible ITO-free OLEDs. We demonstrate, that using PEDOT:PSS anodes rather than ITO on PET leads to completely different optical loss channels and light management challenges within these flexible OLEDs. In most of these devices additional barrier layers are used to prevent permeation of oxygen and moisture into the device, since PET is highly hygroscopic. Here we show that such a barrier layer can act as a low-index layer and leads to a characteristic angle distribution of the light trapped within the substrate and a non-uniform emission. We demonstrate two different approaches to significantly enhance the outcoupling in flexible OLEDs. Firstly, we use titania nanoparticles in a poly(methyl methacrylate) (PMMA) matrix to achieve an index variation in the PMMA and scattering at the substrate air interface. Secondly, we utilize flexible microlens arrays (MLAs) to significantly enhance the outcoupling in our devices. In addition we characterize the devices in the flat and the bent states. Our experimental findings are in good agreement with optical simulations.

9183-76, Session PWed

Synthesis and characterization of heteroatom-bridged bisspirobifluorenes for the application of organic light-emitting diodes

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Pure 2-iodo-9,9'-spirobifluorene was facilely synthesized by an efficient method without troublesome iodination of 9,9-spirobifluorene or Sandmeyer reaction of 2-amino-9,9'-spirobifluorene. A new series of bis-9,9'-spirobifluorene derivatives (SP2X) were synthesized via coupling reactions of 2-iodo-9,9'-spirobifluorene and main group element-containing precursors, such as phenylamine bridged SP2N, ether bridged

SP2O and sulfone bridged SP2SO2. The diphenylsilane bridged of SP2Si and phenylphosphine oxdie bridged SP2PO were facially synthesized from treating lithium-halogen exchanged 2-bromo-9,9-spirobifluorene with dichlorodiphenylsilane and dichlorophenylphosphine, respectively. For possible application for organic light-emitting diodes (OLEDs), the photophysical and thermal properties of SP2X series were studied. The UV-visible absorption and photoluminescence (PL) spectra of SP2X series were studied in dichloromethane. Triplet energy level of these fluorescent SP2X series is vital for the applied phosphorescence dopants and it is determined by low temperature, thin film, time delayed emission spectroscopy. The thermal properties of SP2X series were characterized by using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) which related to the morphological stability of SP2X in thin film state. High fluorescence quantum yield and short fluorescence wavelength enable the materials in the constitution of singlet-triplet hybrid system in white OLEDs (WOLEDs). Finally, bipolar structure nature of SP2X series is beneficial for the balanced charge transport and hence the efficiency of the PHOLEDs. Corresponding charge carrier mobility has been characterized by the comparison of the single carrier devices. A series of OLED devices were fabricated in dopant configurations using SP2X series as host material and the results are presented herein.

9183-77, Session PWed

High barrier properties of transparent thin-film encapsulations for top-emission organic light-emitting diodes

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This paper reported a low-temperature thin film encapsulation (TFE) process based on atomic layer deposition Al2O3 layer for top-emission organic light-emitting devices. The barrier characteristics of both H2O-based and O3-based Al2O3 films were investigated. O3-based Al2O3 TFE showed lower WVTR of 8.7?10-6 g/m2 day and longer continuous operation lifetime of 2.5 folds compared to the device with H2O-based Al2O3 TFE under identical environmental and driving conditions. Furthermore, the extraction of emitting light of the devices with barrier layer were enhanced compared to the bared one. The theory simulation data were consistent with our experimental results and showed the potential for the design of TFE structures optimized for enhancing light extraction.

9183-78, Session PWed

Extremely high efficiency phosphorescent organic light-emitting diodes with horizontal emitting dipoles

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The efficiency of conventional bottom-emitting organic light-emitting diodes (OLEDs) has been steadily improved during the last few decades achieving an external quantum efficiency (EQE) of about 30% in green, 30% in blue, 25-26% in red and 25% in white OLEDs in recent years. Under the assumption that the emitting dipoles exhibit isotropic orientation, the theoretical limit of the EQE of OLEDs is approximately 30%. Therefore, the recently reported EQE of OLEDs seems to have reached its ultimate limit. However, it has been recognized in recent years that some phosphorescent dyes can have preferred orientations. The outcoupling efficiency of the emitted light from the horizontally oriented transition dipole moments of emitters can be much higher than isotropic ones. However, the factors influencing the orientation of the phosphorescent dyes in phosphorescent OLEDs have not been reported yet. Here, we found that the ancillary ligand of phosphorescent dyes significantly influences the dipole orientation. Using the Ir(ppy)2tmd as the dopant, we could realize a bottom emission OLED with the maximum EQE of 32.3% and the maximum power efficiency of 142 lm/W, the highest values ever reported in literature. Furthermore, we experimentally and theoretically correlated the EQE of OLEDs to the PL quantum yield and the horizontal dipole ratio of phosphorescent dyes using three different dyes.

9183-79, Session PWed

Highly efficient inverted top emitting organic light emitting diodes using a transparent top electrode with color stability on viewing angle

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Organic light emitting diodes (OLEDs) are moving toward flexible displays on plastics where low temperature processing is preferred. Inverted OLEDs with a bottom cathode are preferred in the case because oxide semiconductors are n-type. In addition, inverted top emitting OLEDs (TEOLEDs) are preferred in small size high resolution active matrix displays to increase the aperture ratio. The strong resonance effect having mostly used for TEOLEDs results in narrowing of emission spectra and the large variation of the emission color with viewing angle, giving one of the disadvantages for display and lighting application. Therefore, we need to improve the efficiency and the color stability with viewing angle simultaneously.

In this study, we report a high efficiency inverted TEOLED with excellent color stability by using indium zinc oxide as the top electrode and HATCN as the buffer layer. An exciplex-forming co-host system doped with the green dopant bis(2-phenylpyridine)iridium(III) acetylacetonate [Ir(ppy)2acac] was adopted as the emitting layer (EML) in the device. The inverted TEOLED showed an external quantum efficiency (EQE) of 23.4% at 1000 cd/m2 corresponding to the current efficiency of 110 cd/A with the variation of $\Delta x=0.02$, $\Delta y=0.02$ in the CIE 1931 coordinates for the viewing angles between 0 and 60° compared to the Ag-electrode based device showed lower efficiencies of the EQE of 13.8%, 73 cd/A, 43 lm/W at 1000 cd/m2. Moreover, the IZO anode based device showed low efficiency roll-off with the EQE value of 21% and the luminous efficiency of 98 cd/A at 10000 cd/m2.

9183-80, Session PWed

Fluorescent OLED overcoming phosphorescent OLED

Jin-Won Sun, Jeong-Hwan Lee, Kwon-Hyeon Kim, Jang-Joo Kim, Seoul National Univ. (Korea, Republic of)

For many years, phosphorescent OLED has been a requisite to achieve high external quantum efficiency due to its promising nature of exciton harvest from triplet channel. Meanwhile fluorescent OLED has been solely relying on the harvest from monotonous singlet channel. Recently, Thermally Activated Delayed Fluorescence(TADF) has been highlighted since the phenomenon enables mimic of phosphorescent OLED with only certain fraction of time delay from Reverse Intersystem Crossing. However, in order to create such environment, the exciplex has been one of the ideal types since the HOMO and LUMO levels lies at different molecules, which often guarantees small value of energy gap between singlet and triplet excited states. Here, we report an exciplex system with an emitter which shows TADF phenomenon stands out with highest external quantum efficiency that has ever been reported as a fluorescent OLED device. This research will certainly assist to alter its industrial trend of dependency on phosphorescent material in spite of their instability and high cost.

9183-81, Session PWed

Mechanism of peel-off of metal thin film for flexible OLED substrate: effect of surface treatment on delamination

Sungjoo Kim, Jong-Lam Lee, Pohang Univ. of Science and Technology (Korea, Republic of)

In order to understanding the mechanism of delamination of thin film from the mother substrate of glass, the glass surface was modified with functional groups of CH3 prior to the deposition of the metal thin film. The HMDS (SAMs) treatment was effective in decreasing the surface free energy, due to the abundant methyl groups, resulting in island shape with a size of ~10 nm due to the agglomeration of metal atom. It was found that there were three kinds of bonds configuration morphology at the surface of delaminated metal film. It means that the delaminating action can be enhanced by incorporating of H2O molecules between O atoms at the glass surface and Si atoms at a functional group in HMDS. The delaminated film was used in the fabrication of OLEDs device, showing the comparable performance with those on glass substrate. These results clearly represent that the pre-treatment of surface prior to the metal deposition must be a promising approach for delaminating metal thin film for flexible substrate.

9183-82, Session PWed

Color rendering index simulation for white organic light emitting diodes

Xiangyu Fu, Chaoyu Xiang, Franky So, Univ. of Florida (United States)

White organic light emitting diodes (WOLEDs) have attracted a lot of attention due to its potential as high efficiency and high quality lighting sources. Most reported WOLEDs use 2 or 3 emitters generate white light. The correlated color temperature (CCT) and color rendering index (CRI) of the mixed light reply on its spectrum power distribution (SPD). In order to achieve the highest CRI at a desired CCT, careful selection of emitters and good control of the relative intensity of each color component is required. In this paper, we conducted computational simulation and calculated the algorithm to maximize the CRI at a large range of CCT using 2 or 3 given color components. We then analyzed how peak FWHMs of the color components affect the CRI of mixed white light. It is shown that when 2 components are used, higher FWHM (>100 nm) is required to achieve a CRI over 90; when 3 components are used, FWHM of 50 nm is sufficient to achieve a CRI over 90, while the peak wavelength has a larger impact on CRI. It is also found that white light with higher FWHMs are more color stable. Considering the intrinsic wider peaks of OLEDs compared with LEDs, these results indicate that OLEDs are better candidates for mixed white light than LED. However when 3 colors are used, the advantage of wider peak is less significant compared to perfectly tuned peak positions. Therefore, by introducing microcavity effect, the peak wavelength of each color component can be carefully tuned to its optimal value, improving the CRI of WOLEDs.

9183-83, Session PWed

Tuning emission colour of hybrid LEDs: the influence of MoO3 thickness

Jorge Costa Dantas Faria, Alasdair J. Campbell, Martyn A. McLachlan, Imperial College London (United Kingdom)

We report on observed changes to the forward emission spectra in inverted hybrid organic-inorganic LEDs (HyLED) consisting of a poly(9,9-dioctylfluorene-alt-benzothiadiazole)/poly (9,9-dioctylfluorene-alt-N-(4-butylphenyl)-diphenylamine) (F8BT/TFB) polymer bilayer through tuning the thickness of the MoO3 hole injection layer. With a 3nm MoO3 layer, a broad yellow emission centred at 550 nm (CIE coordinate 0.46, 0.52) was observed, with a 15 nm layer the emission narrows considerably and shifts to 542 nm (CIE coordinate 0.34, 0.63). Devices were shown to be stable over multiple testing runs and little variation in device efficiency was observed across the MoO3 thickness range although a slight reduction in turn-on voltage was observed as the MoO3 thickness increased.

We explain the observed changes in emission spectra by considering MoO3 as an optical spacer, whilst also observing the impact on the light out-coupling as the morphology of the MoO3 and F8BT layers change – the former due to the increasing layer thickness, and the latter due to post-deposition annealing conditions. HyLEDs have been previously reported in literature as possessing superior lifetime and stability characteristics with respect to top-cathode, low-workfunction OLEDs and PLEDs. With the observations presented here, the potential tunability of such inverted HyLED devices is increased. By changing the size of the MoO3 layer thickness, we demonstrate a simple, effective method of tuning the emission spectra not previously reported for HyLEDs.

1. R. Liu et al., Appl. Phys. Lett. 99, 093305 (2011)

2. D. Kabra et al., Adv. Mater. 20, 3447-3452 (2008)

9183-84, Session PWed

To enhance light extraction of OLED devices by multi-optic layers including a micro lens array

Jen-Chi Lee, Chao-Heng Chien, Tatung Univ. (Taiwan); Chuang-Hung Chiu, Chunghwa Picture Tubes, Ltd. (Taiwan); Yu-Xaong Kuo, Tatung Univ. (Taiwan)

In recent years, OLED has advantages including that larger light area, thinner thickness, excellent light uniformity, and can be as a flexible light source. Many display panel and lighting have been started to use the OLED due to OLED without back light system, thus how to make and employ light extracting layer could be important issue to enhance OLED brightness. The purpose of this study is to enhance the light extraction efficiency and light emitting area of OLED, so the light extracting film includes micro lens array and the prism reflection layer were provided to enhance the surface light extracting efficiency of OLD. Finally the prism layer and diffusing layer were used to increase the uniformity of emitting area of OLED, which the efficiency of 31% increasing to compare with the OLED without light extracting film.

9183-85, Session PWed

Correlating the transition dipole moment orientation of phosphorescent emitter molecules in organic light-emitting diodes (OLEDs) to basic material properties

Arko Graf, Philipp Liehm, Technische Univ. Dresden (Germany) and Univ. of St. Andrews (United Kingdom); Caroline Murawski, Simone Hofmann, Karl Leo, Technische Univ. Dresden (Germany); Malte C. Gather, Univ. of St. Andrews (United Kingdom) and Technische Univ. Dresden (Germany)

The emission from individual molecules in the emissive layer of OLEDs can be described as oscillating dipole. The orientation of the associated transition dipole moment strongly affects the efficiency of light extraction from the OLED. Molecules with horizontally oriented transition dipole moments show increased light extraction. Simulations indicate that 1.5-fold efficiency enhancements are feasible by orientating the dipoles in an OLED. Recently, the average dipole orientation of the phosphorescent emitters Ir(ppy)3, Ir(ppy)2(acac), and Ir(MDQ)2(acac) was studied in detail. While the transition dipole orientation of Ir(ppy)3 was found to be isotropic, preferentially horizontal orientation was observed for Ir(ppy)2(acac) and Ir(MDQ)2(acac).

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Here, we compare the orientation of the emissive dipole moment of seven Iridium-based emitter molecules by measuring the angle dependent spectral radiant intensity of the emission from OLEDs comprising these emitters. These data are compared to optical simulations that include a parameter describing the average dipole orientation. By minimizing the least square error between simulation and experiment, the actual orientation is determined. Surprisingly, amongst the emitters studied, isotropic orientation is the exception; most emitters show considerable horizontal orientation. To better understand this observation and to identify ways of predicting transition dipole orientation of emissive molecules, we calculate the permanent dipole moment of the most abundant isomer of each emitter using density functional theory. This yields a parameter that correctly predicts –at least for the emitters investigated here– whether the average transition dipole moment is isotropic or horizontal. Possible explanations for this correlation are discussed.

9183-86, Session PWed

High efficiency ITO-free phosphorescent organic light emitting diodes with wide viewing angles

Soniya D. Yambem, Mujeeb Ullah, Ebinazar B. Namdas, Paul L. Burn, The Univ. of Queensland (Australia)

Organic light emitting diodes (OLEDs) have significantly advanced in the last decade by virtue of them being light weight, flexible, extremely thin, and having high colour contrast and efficiency. However, increasing the out-coupling efficiency of the generated light continues to be a challenge. Conventionally, OLEDs have a bottom emitting structure with Indium Tin oxide (ITO) as the transparent anode. Due to the differences in the refractive indices of the constituent material only around 20% of the generated light is out-coupled from the front of the device. Therefore, increasing the out-coupling of generated light is an important goal for OLEDs, with strategies reported including structuring of the electrodes, inclusion of photonic crystals, using top emitting architectures, modification of refractive indices and controlling the air-substrate structure using, for example, micro lens arrays. Here we present an ITO-free high efficiency OLED using a simple planar top emitting structure. A multilayer anode comprising MoOx(5nm)/Ag (10 nm)/MoOx (40 nm) (a MAM stack) was used while Ir(PPy)3:CBP was used as the emissive layer. The device has a structure: substrate/Al/LiF/TPBi/Ir(PPy)3:CBP/MAM. We show that the current and external quantum efficiencies reached a maximum of 84.5 cd/A and 22.6 %, respectively. The efficiencies of the current architecture surpassed the reported efficiencies of earlier phosphorescent OLEDs in which the MAMs were used within the cathode. Furthermore, we demonstrate that the emission spectrum, and therefore color of the current MAM-based OLED, stays constant for a wide viewing angle, up to 70 degrees, making it highly suitable for application in display technologies.

9183-87, Session PWed

Ultra thin layer p-doping and band bending in C60 on MoOx

Chenggong Wang, Univ. of Rochester (United States); Xiaoliang Liu, Central South Univ. (China); Yongli Gao, Univ. of Rochester (United States)

The electronic energy level evolution of fullerene (C60) on molybdenum oxide (MoOx)/C60 interfaces has been investigated with ultra-violet photoemission spectroscopy (UPS) and X-ray photoemission spectroscopy (XPS). It was found that there was a band bending of ultra-thin layer MoOx (10 Å) on the C60. With the deposition of C60 on the top of ultra-thin layer of MoOx, the strong p-doping was observed in C60 and the band bending was observed as well. The highest occupied molecular orbit (HOMO) of C60 layer pinned at the Fermi level.

9183-88, Session PWed

Virtual screening for OLED materials

Mathew D. Halls, David J. Giesen, Thomas F. Hughes, Alexander Goldberg, Yixiang Cao, H. Shaun Kwak, Schrödinger, Inc. (United States); Jacob Gavartin, Schrödinger, Inc. (United Kingdom)

Organic light-emitting diodes (OLEDs) are under widespread investigation to displace or complement inorganic optoelectronic devices for solid-state lighting and active displays. The materials comprising the active layers in OLED devices are selected or designed to provide the required intrinsic and extrinsic electronic properties needed for efficient charge injection and transport, and desired stability and emissive properties. The chemical design space for OLED materials is enormous and there is need for the development of computational approaches to help identify the most promising chemical solutions for experimental development. In this presentation we will present a multi-scale simulation approach to efficiently screen libraries of potential OLED molecular materials. The workflow to assess potential OLED materials is: 1) evaluation based on first-principles prediction of key intrinsic properties (EHOMO, ELUMO, ?e/h, Etriplet), 2) classical simulation of thin film morphology (RDF, ?), and 3) first-principles evaluation of electron coupling for donor-acceptor pairs (Hab) from the simulated condensed phase morphology.

9183-89, Session PWed

Energy transfer in organic light emitting diodes

Grayson Ingram, Zhenghong Lu, Univ. of Toronto (Canada)

As the performance of organic light emitting diodes (OLEDs) continues to improve and devices become more complex to meet the demands for solid state lighting, an understanding of the underlying device physics becomes increasingly important. In order to produce white OLEDs for solid state lighting applications, a fluorescent host is doped with multiple emitting molecules with different characteristic wavelengths. In most highly efficient OLEDs, one or all of the emitting molecules are phosphors so that both singlet and triplet excitons may be harvested. Managing the color balance between these emitting molecules is a difficult process involving managing diffusion to, and energy transfer between, the emitting molecules. The energy transfer will typically occur through a long range Forster resonant energy transfer (FRET). Here, FRET between a common phosphorescent emitter and intentionally introduced exciton quenching centers is investigated by varying the distance between phosphorescent and quenching layers in a functional OLED. Using this platform we are able to probe the exciton distribution inside the OLED. A unique device architecture is used to isolate the effects of FRET. The results are shown to agree with theory and improve the understanding of the fundamental process of energy transfer. We expect that this work will provide an invaluable tool for studying excitons in organic light emitting diodes.

9183-90, Session PWed

Sensitized fluorescence in organic light emitting diodes

Carmen Nguyen, Grayson Ingram, Zhenghong Lu, Univ. of Toronto (Canada)

We study the effects of incorporating phosphorescent sensitizers into fluorescent organic-light emitting diode (OLED) devices. In the emissive layer of this system, the host material is co-doped at low concentrations with both a phosphorescent and a fluorescent dye. The purpose of the phosphorescent dopant is to capture both singlet and triplet excitons from the host material and to transfer them into the singlet state of the fluorescent dye. Ideally, Recombination of excitons and the emission of light would occur solely on the fluorescent dye. This sensitized fluorescent system could potentially achieve 100% internal quantum

efficiency as both triplet and singlet states are being harvested. We have observed an almost two-fold improvement in the quantum efficiency of a sensitized fluorescent system, utilizing rubrene as the fluorescent dye and Ir(ppy)2(acac) as the sensitizer, versus a standard rubrene-based host-guest system. By testing various dopant concentrations, the optimal emissive layer composition for this system was determine to be ~2 wt.% rubrene and ~7 wt.% Ir(ppy)2(acac) in a CBP host. Other sensitized fluorescent systems are also being investigated to achieve a host-sensitizer-fluorescent dye combination that best realizes the ideal sensitized fluorescent mechanism. This system would exhibit high efficiency Förster energy transfer of triplet states from the phosphorescent sensitizer to the singlet state of the fluorescent dye while minimizing undesirable effects such as direct exciton formation on the fluorescent dopant.

9184-303, Session Plen

Organic Solar Cells: From a Lab Curiosity to a Serious Photovoltaic Technology

Karl Leo, Technische Univ. Dresden (Germany) and King Abdullah Univ. of Science and Technology (KAUST) (Saudi Arabia)

Carbon-based organic semiconductors have many potential advantages like easy large-area preparation on flexible substrates, large variety of materials, and low cost. Organic solar cells have recently achieved significant progress and have crossed the 10% efficiency mark. In this talk, I will present an overview over the key features of solid-state organic solar cells and recent developments in the field. One central research area is the design of the bulk heterojunction active layer, requiring a nanoscale phase separation and optimized morphology to achieve efficient operation. I will also discuss highly efficient tandem structures with optimized electrical and optical properties, having the potential for approx. 20%.

9184-1, Session 1

Materials and device architectures for multi-junction polymer solar cells *(Keynote Presentation)*

René A. J. Janssen, Technische Univ. Eindhoven (Netherlands)

No Abstract Available

9184-2, Session 1

Incorporating multiple absorbers to improve spectral absorption in high efficiency organic solar cells *(Invited Paper)*

Barry P. Rand, Princeton Univ. (United States); David Cheyns, Kjell Cnops, IMEC (Belgium); Bregt Verreet, Princeton Univ. (United States)

Organic-based solar cells are beginning to emerge with the potential to compete with other low-cost thin film photovoltaic technologies, with efficiencies of 12% recently demonstrated. Here, I will focus on two device architectures that allow for broad absorption to enable efficiencies to continue to improve: tandem cells and cascade architectures.

First, I will discuss our recent efforts to utilize high (1.8 eV) and low (1.4 eV) optical gap subcells in a complementary absorbing tandem cell. In the high energy absorbing subcell, fullerene (C70) dominates the photoresponse, whereas the low energy absorption is provided by a donor-acceptor molecule. Optimization of the tandem cell allows us to reach an efficiency of 7.3%, 30% higher than either of the subcells, while the fill factor of the tandem cell is able to exceed the value of either of the subcells.

The other aspect concerns investigating highly efficient fullerene-free devices in a cascade device architecture, an alternative structure to the tandem cell that still enables the use of multiple complementary absorbers. Proper optimization to eliminate parasitic quenching effects, increase open-circuit voltage, and utilize Forster resonance energy transfer has enabled us to demonstrate certified state-of-the-art evaporated single cells (whether with or without fullerene) of 8.4% in a fullerene-free device.

9184-3, Session 1

The power of materials science tools for gaining insights in organic photovoltaic devices *(Invited Paper)*

Natalie Stingelin, Imperial College London (United Kingdom)

In the past decade, significant progress has been made in the fabrication of organic photovoltaic devices predominantly due to important improvements of existing materials and the creation of a wealth of novel compounds. Many challenges, however, still exist. Real understanding of what structural and electronic features determine the short-circuit current (Jsc), open-circuit voltage (Voc) and fill factor (FF) are often still lacking; and the role of charge transfer (CT) states and which CT states are critical for efficient charge generation are currently heavily debated. Here we attempt to obtain further insight of relevant structure/ processing/ performance interrelations using classical polymer processing 'tools'. We present a survey on the principles of structure development from the liquid phase of this material family with focus on how to manipulate their phase transformations and solid-state order to tailor and tune the final 'morphology' that allow establish correlations with relevant device characteristics. This will include discussions on how the presence of intermixed phase relates to CT absorption; how we can manipulate the CT energy; and what structural features seem to influence Voc.

9184-4, Session 1

Organic solar cells with non-fullerene acceptors *(Invited Paper)*

Michael L. Chabinyc, Univ. of California, Santa Barbara (United States)

While solar cells with fullerenes have shown high efficiencies, the inability to tune the electronic levels of fullerene limits the open circuit voltage, so alternative acceptors are desirable. We will present results on morphological and optoelectronic studies on bulk heterojunctions of a novel non-fullerene acceptor, decacyclene triimide (DTI) with P3HT and low band gap semiconducting polymers. DTI forms BHJs with power conversion efficiencies above 1% with these polymers with high open circuit voltages. These values lag those of fullerenes, but reveal important details about charge transfer processes because DTI exhibits efficient channel I and II photocurrent. X-ray scattering and absorption spectroscopy reveals that the molecular orientation of DTI is limiting its performance rather than an intrinsic molecular property. The role of molecular orientation on the performance of non-fullerene acceptors will be discussed along with design considerations for next generation materials.

9184-5, Session 2

Cyanine dyes in solid state organic heterojunction solar cells *(Invited Paper)*

Jakob Heier, Chuyao Peng, Anna C Véron, Thomas Geiger, Roland Hany, Frank A Nüesch, EMPA (Switzerland); Marcus V. G. Vismara, Carlos F. O. Graeff, Univ. Estadual Paulista "Júlio de Mesquita Filho" (Brazil)

Today numerous soluble cyanine dyes are available, driven by more than a century of research and development of the photographic industry. Numerous properties specific to cyanine dyes suggest that this material class can be of interest for organic solar cell applications. The main absorption wavelength can be tuned from the ultra-violet to the near-infrared. The unparalleled high absorption coefficients allow using very thin films for harvesting the solar photons. Furthermore, cyanines are

cationic polymethine dyes, offering the possibility to modify the materials by defining the counter-anion. We here show specifically how counter-ions can be utilized to tune the bulk morphology when blended with PCBM. We compare the performance of bilayer heterojunction and bulk heterojunction solar cells for two different dyes absorbing in the visible and the near-infrared.

Charge transfers of light induced excitons between cyanine dyes with different counter-ions and MEH-PPV, C60 and PCBM are studied using Light-induced Electron Spin Resonance (LESR) at different temperatures. Measurements were performed using pure materials and mixtures (1:1 wt %). For the pure dyes no (L)ESR signal was observed. For mixtures at least two signals were observed, one associated with the dye in g ~ 2.002 and the other associated with the polymer (g ~2.004) or C60/PCBM (g ~1.999). These two signals stem from the photogenerated positive and negative polarons on MEH-PPV and cyanine dyes, respectively. For the cyanine dyes with C60 or PCMB, the LESR signals observed come from the photogenerated positive polaron of the cyanine and the negative polaron of buckminsterfullerene derivates.

9184-6, Session 2

Thiophene-thiazolothiazole copolymers: significant impact of side chain composition on backbone orientation and solar cell performances

Itaru Osaka, RIKEN (Japan); Masahiko Saito, Hiroshima Univ. (Japan); Tomoyuki Koganezawa, Japan Synchrotron Radiation Research Institute (Japan); Kazuo Takimiya, RIKEN (Japan)

In this presentation, we report on a series of thiophene–thiazolothiazole copolymers with various compositions of linear and branched alkyl side chains. Either in the polymers with both linear and branched groups (linear–branched) and with only branched groups (all-branched), careful choice of the length of two alkyl groups allows us to control the polymer orientation from edge-on to face-on. It is interesting to note that although in all cases the polymer orientation turns into face-on when blended with fullerene, photovoltaic performances of the polymer-based solar cells are greatly affected by the primary orientation observed in the polymer-only films. The “face-on polymers” preserve FF relatively high, even when the active layer become thick, while they show an increase of short-circuit current, overall leading to an increase of PCE. In the meantime, the “edge-on polymers” show a significant drop of FF particularly when the layer is beyond 200 nm, and thus a decrease of PCE. In addition, the composition of the side chains is also found to impact on another photovoltaic parameter; the “all-branched polymers” provide higher open-circuit voltages (Voc) as compared to the “linear–branched polymers”, though the composition does not affect the HOMO energy level. Consequently, a polymer with all-branched alkyl groups that forms crystalline face-on structure reached PCEs as high as 7.5%, with a high Voc of 0.90 V at the active layer thickness of 330 nm. Furthermore, PCEs of close to 6% was observed with extraordinarily thick layers of up to 1 μm.

9184-7, Session 2

Organic OPV materials with enhanced charge separating properties *(Invited Paper)*

Fatemeh Jahani Bahnamiri, Solmaz Torabi, Hilde D. de Gier, Evgenia Douvogianni, Univ. of Groningen (Netherlands); Remco W. A. Havenith, Univ. of Groningen (Netherlands) and Univ. Gent (Belgium); Ryan C. Chiechi, Lambert J. A. Koster, Jan C. Hummelen, Univ. of Groningen (Netherlands)

We have recently predicted that when the dielectric constant of organic semiconductors is increased from 2-4 to about 10, a dramatic increase in (maximal) power conversion efficiency of organic solar cells, based on these materials as active layer constituents, can be achieved.1 Binding energies of initial excitons, of charge transfer excitons, and between charges in any type of recombination process are diminished with increasing electric permittivity of the medium.

In order to design and develop new molecular materials with higher dielectric constant, the next challenge is to make the connection between the dielectric constant, as a macroscopic property, and molecular structure.

One approach is to connect suitable substituents to known (opto) electronically functional molecular moieties. We report here on the design and preparation of molecules bearing substituents that are to enhance the dielectric properties without diminishing other crucial parameters (like charge carrier mobility, bandgap, stability, etc.).

Through a computational chemistry approach, we investigate the influence of molecular moieties on the relative energies of various charge separated states resulting from photo-induced charge transfer between molecular donors and acceptors. We report on a system in which the energies of the charge separated states are tuned to a favorable situation by proper placement of dipolar substituents.

1. L. J. A. Koster, S.E. Shaheen, J.C. Hummelen, Adv. Energy Mater. 2012, 2, 1246.

9184-8, Session 2

Semi-crystalline low band gap polymers for highly efficient organic photovoltaic cells

Han Young Woo, Thanh Luan Nguyen, Mohammad Afsar Uddin, Pusan National Univ. (Korea, Republic of)

Despite recent remarkable progresses in polymer solar cells (PSCs), the development of highly efficient and thermally stable PSCs have been still challenging. This study reports highly efficient new LBG photovoltaic structures with a planar polymeric backbone formed via noncovalent intra- and inter-chain attractive interactions, leading to highly crystalline morphology in the film, deep HOMO level, ideally balanced electron and hole mobility and exceptional device stability. The crystalline polymers formed a well-distributed fibrillar networked morphology with PC70BM with an ideally balanced hole and electron mobility (with e/h mobility ratio of nearly 1 for PPDT2FBT:PC70BM). Furthermore, methanol treatment of the optimized devices demonstrated efficiency of over 9% in a conventional single-cell device structure without any functional layer. In addition, the devices based on these polymers exhibited ~7% PCE and outstanding long-term thermal stability at 130 oC over 200 h in a conventional PSC having a single-cell device structure without any processing additives and interfacial layer.

9184-9, Session 2

Solution-processible perylene diimide based star-shaped small molecule acceptor: Synthesis and photovoltaic properties

Xin Zhang, Bo Jiang, Shaoqing Zhang, Jianhui Hou, Jiannian Yao, Institute of Chemistry, CAS (China); Chuanlang Zhan, Institute of Chemistry (China)

As alternative to the commonly used acceptor materials of PCBM, non-fullerene small molecule acceptors have been gained increasing interest in the organic solar cell community. Perylene diimide (PDI) derivatives are promising candidates because of their excellent optoelectronic properties such as wide spectral converage, strong absorption in the visible spectral region, excellent electron affinity and mobility. While, when using as the acceptor material in the solution-processed organic solar cells, their over-strong aggregation ability becomes a bottleneck, severely limiting the photon-to-electron conversion efficiency. In this report, I will present a series of solution-processed dimeric PDIs, which show high efficiency (>4%) with exciting short-circuit current density and fill factor when blended with either polymer or small molecule donors.

[1] (a) X. Zhang, Z. H. Lu, L. Ye, C. L. Zhan, J. H. Hou, S. Q. Zhang, B. Jiang, Y. Zhao, J. H. Huang, S. L. Zhang, Y. Liu, Q. Shi, Y. Q. Liu, J. N. Yao, Adv. Mater., 25, 5791 (2013). (b) B. Jiang, X. Zhang, C. L. Zhan, Z. H. Lu, J. H. Huang, X. L. Ding, S. G. He, J. N. Yao, Polym. Chem., 4, 4631 (2013). (c) Z. H. Lu, X. Zhang, C. L. Zhan, B. Jiang, X. L. Zhang, L. L. Chen, J. N. Yao, Phem. Chem. Chem. Phys., 15, 11375, (2013).

9184-10, Session 3

Spatially resolving ultrafast exciton dynamics in organic semiconducting thin films *(Invited Paper)*

Naomi S. Ginsberg, Cathy Y. Wong, Benjamin L. Cotts, Samuel B. Penwell, Hao Wu, Rodrigo J. Noriega-Manez, Univ. of California, Berkeley (United States)

In solid state semiconducting molecular materials used in electro-optical applications, relatively long exciton diffusion lengths hold the promise to boost device performance by relaxing proximity constraints on the locations for light absorption and interfacial charge separation. The architecture of such materials determines their optical and electronic properties as a result of spacing- and orientation-dependent Coulomb couplings between adjacent molecules. Exciton character and dynamics are generally inferred from bulk optical measurements, which can present a severe limitation on our understanding of these films because their constituent molecules are neither perfectly ordered nor perfectly disordered. Nevertheless, such microstructure can have profound impacts on transport properties.

The ultrafast spectroscopy of single domains of polycrystalline films of TIPS-pentacene, a small-molecule organic semiconductor of interest in electronic and photovoltaic applications, is investigated using transient absorption microscopy. Individual domains are distinguished by their different polarization-dependent linear and nonlinear optical responses. As compared to bulk measurements, we show that the nonlinear response within a given domain can be tied more concretely to specific physical processes that transfer exciton populations between specified electronic states. By use of this approach and a simple kinetic model, the signatures of singlet fission as well as vibrational relaxation of the initially excited singlet state are identified. As such, observing exciton dynamics within and comparing exciton dynamics between different TIPS-pentacene domains reveal the relationship between photophysics and film morphology and the potential to resolve unique signatures at domain boundaries, where significant exciton or charge trapping may occur.

9184-82, Session 3

Using Monte Carlo modeling to reconcile conflicting experimental reports of the origin of efficient charge generation in organic solar cells

Timothy M. Burke, Michael D. McGehee, Stanford Univ. (United States)

Recent advances in Organic Photovoltaics have led to single junction device efficiencies over 9%. However, an incomplete understanding of the fundamental photophysical processes that enable high performance in some material systems while yielding low performance in numerous others slows the pace of this continued innovation.

Various explanations have been proposed for the physical mechanisms that lead to high performance including ultrafast electron delocalization on fullerene clusters, hot carrier effects, microscopic material polarization and energy cascades caused by molecular aggregation. In this work we use Kinetic Monte Carlo (KMC) modeling, equilibrium statistical mechanics calculations, explicit Markov Chain methods and ensemble Metropolis Monte Carlo to reconcile these conflicting results.

We use KMC supported by time-resolved terahertz spectroscopy measurements to show that nanoscale carrier mobilities and geminate pair lifetimes in OPV systems are compatible with >90% internal quantum efficiencies, even when starting from thermally-relaxed Charge Transfer (CT) states. We further show that energetic disorder leads to an ultrafast and temperature independent carrier separation over several nanometers, as reported experimentally, but, critically, we find that this separation only weakly affects the geminate splitting probability and that the carriers are still tightly bound at this distance, arguing against the claim that ultrafast delocalization drives efficient geminate splitting. Using a novel Markov Chain technique we show that the geminate splitting probability increases only slightly from 1nm to 6nm separation. This result reconciles hot exciton and pump-push-probe experimental results implying a separation dependence with sub-bandgap EQE measurements showing high efficiency upon direct CT state excitation.

9184-11, Session 4

Charge recombination in solution-processed small molecule bulk heterojunction solar cells *(Invited Paper)*

Thuc-Quyen Nguyen, Univ. of California, Santa Barbara (United States)

In this study, we investigate charge transport and nongeminate recombination in two solution processed small molecule bulk heterojunction solar cells consisting of diketopyrrolopyrrole (DPP) based donor molecules, mono-DPP and bis-DPP, blended with [6,6] phenyl-C71-butyric acid methyl ester (PCBM). While the bis-DPP system exhibits a high fill factor (62%) the mono-DPP system suffers from pronounced voltage dependent losses which limit both the fill factor (46%) and short circuit current. Time delayed collection field (TDCF) experiments reveal the voltage dependence of geminate recombination of the mono-DPP:PCBM system. By analyzing impedance spectra and light intensity measurements of the current-voltage characteristics indicate that the mono-DPP system is severely limited by nongeminate recombination losses in addition to the geminate recombination. The effective carrier lifetime in the bis-DPP system is observed to be at least twice that in the mono-DPP system. Further analysis reveals that the most significant factor leading to the difference in fill factor is the comparatively poor hole transport properties in the mono-DPP system. These results suggest that future design of donor molecules for organic photovoltaics should aim to increase charge carrier mobility thereby enabling faster sweep out of charge carriers before they are lost to nongeminate recombination.

9184-12, Session 4

Hot photocarrier dynamics in organic semiconductors studied by ultrafast terahertz photoconductivity and transient absorption *(Invited Paper)*

Paul A. Lane, Paul D. Cunningham, Joseph S. Melinger, U.S. Naval Research Lab. (United States); Edwin J. Heilweil, National Institute of Standards and Technology (United States)

We studied the dynamics of hot photocarriers in organic solar cells. Charge transfer from excited donors generates hot carriers with excess energy arising from the electron affinity offset of the donor (ZnPc or 6T) and acceptor (C60). Hot carriers manifest themselves through terahertz photoconductivity that decays on a ps time scale as carriers thermalize. Different dynamics are observed when exciting acceptors near their absorption edge. Charge transfer generates thermalized carriers described by terahertz photoconductivity dynamics consisting of an instrument-limited rise to a long-lived signal. Excess excitation energy is thus directly linked to carrier mobility.

9184-13, Session 4

Transport of hot carriers in polymer-based organic solar cells

Almantas Pivrikas, The Univ. of Queensland (Australia)

We have studied the impact of excess photon energy on excitonic dissociation efficiency in operational and efficient solar cells. We show that hot excitons are not beneficial for operational solar cells, because Internal Quantum Efficiency (IQE) is independent of photon energy [1]. IQE is observed to be essentially flat with no appreciable benefit from higher-energy photons. We demonstrate that methodology of IQE measurement is crucially important for unambiguous result interpretation and clarify the impact of optical interference effects and light absorption in the non-active layers in thin operational devices. An attention is directed to the importance of treating an OSC as a complex optical cavity.

Second, we show the impact of excess photon energy on charge transport in several efficient polymer-based photovoltaic devices. Charge extraction is observed to be independent on photon energy suggesting that excitons lose their excess energy at times scales which are much shorter than the time scales of charge extraction [3]. Moreover, we show that the charge carrier thermalization effects can be neglected in operational solar cells, while charge carrier density loss during transport due to capture by trap states is crucial for efficient device operation. The impact of these results in regards to the present knowledge of charge transport is discussed.

Finally, a number of novel techniques developed for the purpose of unambiguous electron and hole mobility measurements in operational devices is presented. A critical conclusion arising from our results demonstrates, in contrasts the commonly accepted knowledge, that efficient solar cells do not need balanced charge carrier mobilities [3]. This message is further elaborated and clarified that balanced mobility become important only in materials with strong non-Langevin recombination. The impact of Langevin and non-Langevin recombination on the photocurrent and fill factors is demonstrated in actual solar cells at near to operational conditions.

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9184-14, Session 4

Using Forster resonance energy transfer to extend spectral harvesting in polymer solar cells

Erik D. Klump, Tzung-han Lai, Franky So, Univ. of Florida (United States)

Polymer solar cells have generated significant attention as a potentially low-cost renewable energy. However, one of the limiting factors that needs to be addressed is the limited region of the solar spectrum that can be efficiently harvested in a single junction polymer solar cell. Recently, a squaraine dye has raised research interest which is demonstrated to enhance the spectral response of PCDTBT solar cells by combining an exceptionally large absorption coefficient with a unique morphology that promotes efficient exciton dissociation.

In this work, it is demonstrated that these squaraine dyes operate in part via Forster resonance energy transfer that transfer the exciton from PCDTBT to squaraine for enhanced exciton dissociation at the squaraine/fullerene interface. This allows small amounts of squaraine dye to increase the internal quantum efficiency of a solar cell by extending the distance within the polymer from which excitons can be harvested. Additionally, with less than 10% squaraine by weight, squaraine extends the spectral harvesting of the PCDTBT solar cells, with external quantum efficiencies exceeding 30% at 720nm. The result is a 15% increase in the overall efficiency from 4.5% to 5.2% for the ternary blend solar cell. In conclusion, efficient exciton transfer via FRET in the ternary blend solar cell is made possible by less than 10% additive which is promising for extending spectral response of OSCs without compromising the efficient bulk heterojunction morphology.

9184-15, Session 5

Tuning photovoltaic performance in donor-acceptor polymers by chemical functionalization *(Invited Paper)*

Martin J. Heeney, Imperial College London (United Kingdom)

The donor-acceptor approach of copolymerizing electron rich and electron poor co-monomers is a promising route to high performance solar cell polymers. In this talk I will discuss how systematic changes to the acceptor unit influence the polymer properties and photovoltaic performance. Polymer analogous reactions, as well as traditional copolymerization of preformed monomers will be compared and contrasted as synthetic routes to control properties.

9184-16, Session 5

Field dependent recombination at low temperatures in an organic photovoltaic blend

Stavros Athanasopoulos, Univ. of Cambridge (United Kingdom); Alexei D. Chepelianskii, Univ. Paris-Sud 11 (France) and Univ. of Cambridge (United Kingdom); Richard H. Friend, Neil C. Greenham, Univ. of Cambridge (United Kingdom)

The transport of charges in disordered molecular materials mediates significant electronic processes that govern the efficiency of organic semiconductor devices. Charge carrier recombination poses an important loss mechanism for organic solar cells while for LEDs it is responsible for the desired electroluminescence[1]. Here we report on the non-trivial field dependence of charge carrier recombination in an organic blend at low temperatures. Using a new microwave technique that monitors the resonance frequency shift of a superconducting resonator[2] we show that an applied electric field can increase the recombination of long-lived carriers in bulk heterojunction P3HT:PCBM blends. To understand this behaviour, we have simulated the long-time dynamics of photo-generated carrier pairs with kinetic Monte Carlo simulations of hopping transport using energetically disordered lattice morphologies with a Gaussian density of states and Miller-Abrahams transition rates that are appropriate for describing charge transport in the non-equilibrium regime[3]. We find that the increase in recombination with electric field is due to carrier pairs at donor-acceptor interfaces with an initial critical separation of at least 5 nm. This rather large initial separation length reveals a new recombination regime where the Coulomb interaction and the external electric field act synergistically to enhance recombination. The above scenario is consistent with recent transient absorption experiments[4] that suggest ultrafast separation of charge-transfer states in polymer:fullerene blends on a several nanometer length-scale within quasi-crystalline fullerene domains.

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9184-17, Session 5

Impedance spectroscopy and large perturbation transient photovoltage: measurement methods for recombination dynamics in organic photovoltaic

James I. Basham, National Institute of Standards and Technology (United States) and The Pennsylvania State Univ. (United States); Lindsay C. C. Elliot, National Institute of Standards and Technology (United States); Kurt P. Pernstich, ETH Zürich (Switzerland); Dean M. DeLongChamp, National Institute of Standards and Technology (United States); Thomas N. Jackson, The Pennsylvania State Univ. (United States); David J. Gundlach, National Institute of Standards and Technology (United States)

Understanding recombination processes in organic photovoltaics is key to further increases in efficiency through eliminating losses. To that end, we present the use of Impedance Spectroscopy and Large Perturbation Transient Photovoltage(LTPV)/Photocurrent as effective, non-destructive means to measure the rate and order of recombination in organic photovoltaics. Both methods independently arrive at the same dependence of lifetime on mobile carrier concentration, ranging from ~ 1 ms at 10^14 carriers cm-3 to 1 ?s above 10^16 cm-3. We also observe 5x1014 fixed charges cm-3. Importantly, it is observed that the mechanism of recombination changes from trap-mediated at low carrier filling to bimolecular at moderate carrier filling. Higher order recombination is observed at illumination intensities greater than 1 Sun. We discuss the instrumentation requirements for LTPV measurements, specifically the extremely high input impedance needed to prevent discharge of the device through the measurement circuit. This is a more stringent requirement than for comparable small signal transient photovoltage measurements, though results in a highly sensitive measurement of the voltage transient over six decades in time. We marry the results with data collected via impedance spectroscopy from intensities as low as 0.001 Sun to above 1 Sun and demonstrate that the two methods measure nearly identical rates and orders of recombination. We find that the microstructure of P3HT:PCBM films can greatly affect recombination dynamics. Geminate recombination, or field-assisted charge extraction is seen to emerge from non-ideal film formation. Ideal films reveal a mobility of 10^-4 cm2V-1s-1 and band tail characteristic energy of 32 meV via Impedance spectroscopy.

9184-18, Session 5

The relationship between charge carrier generation pathway and internal quantum efficiency

Ardalan Armin, Ivan Kassal, Paul E. Shaw, Mike Hambsch, Martin Stolterfoht, The Univ. of Queensland (Australia); Jun M. Li, A*STAR Institute of Materials Research and Engineering (Singapore); Paul L. Burn, Paul Meredith, The Univ. of Queensland (Australia)

The conventional picture for the operation of an organic solar cell casts the polymer as the primary photon absorber with free carriers subsequently generated following electron transfer from the polymer to a fullerene (channel I). However, the development of low optical gap polymers and in particular the use of PC71BM has led to considerable revision of this model. It is increasingly clear that the PC71BM is not just an electron acceptor and transport material but also contributes directly to the photocurrent through photoexcited hole transfer (channel II).

We report the results of an investigation into the process of charge generation in blends of low optical gap polymers with PCBM. Devices incorporating PCDTBT:PC71BM, PCPDTBT:PC71BM and PCPDTBT:PC61BM blends all exhibit an internal quantum efficiency (IQE) that when corrected for optical effects is independent of wavelength. This shows not only that the generation efficiency is independent of excess energy but also that both channel I and II are equally efficient, most likely because they share the same interfacial CT state. In contrast the IQE of DPP-DTT:PC71BM devices exhibits two flat regions with the IQE greatest at shorter wavelengths where the fullerene is the dominant absorber. Using photoinduced absorption spectroscopy we show that this difference is caused by a decrease in the efficiency of the channel I process, resulting in reduced charge carrier generation. These results highlight the importance of considering the energetics of both channel I and channel II processes in understanding device performance.

9184-19, Session 5

Carrier-selectivity limit on recombination dynamics of organic photovoltaics

Kilwon Cho, Pohang Univ. of Science and Technology (Korea, Republic of)

Interfacial energetics determines the performance of organic photovoltaic cells (OPVs) based on a thin film of organic semiconductor blends. The charge carrier recombination and internal field formation can be severely influenced by efficient charge carrier extraction at the desired electrode. Here, several approaches for tailoring charge collecting interfaces for highly efficient OPVs are discussed. The n-type metal oxide semiconductor and functional polymeric insulator blends are introduced as a cathode interlayer to promote carrier selective Ohmic contact at metal-organic interface. Along with the highly rectifying nature of wide-bandgap metal-oxide semiconductor, the addition of insulating polymer significantly reduced the diffusion and recombination of minority carrier in the vicinity of electrode, which, in this case, is the hole carrier near cathode. The resultant device performance showed significantly increased shunt resistance accompanied by shift in photovoltage. To quantitatively assess the carrier-selective contact limit on the charge carrier dynamics, dipole moment within the interfacial layer was gradually tuned by introducing a ferroelectric polymer. The transient photovoltaic responses showed a significant variation of the non-geminate recombination rate depending on the degree of rectification of photogenerated carrier within the blend. These results show that the carrier selectivity at the electrode mainly decides the fate of diffusive charge carrier near open-circuit condition. In addition, the systematic study on the effect of deviation from the Ohmic contact regime by various photoactive materials was also performed. Due to the simplicity and the excellent performance, the introduction of the carrier selective interfacial layer could be a new platform for the tunable interfacial energetics for high performance printed OPV devices.

9184-20, Session 5

Decreased recombination from light induced traps by increasing polymer crystallinity in bulk heterojunction solar cells

Thomas Heumueller, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany) and Stanford Univ. (United States); William R. Mateker, Isaac T. Sachs-Quintana, Koen Vandewal, Jonathan A. Bartelt, Stanford Univ. (United States); Christoph J. Brabec, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany) and Bayerisches Zentrum für Angewandte Energieforschung e.V. (Germany); Michael D. McGehee, Stanford Univ. (United States)

On the way to commercialize organic photovoltaic solar cells fast initial performance losses present in many high efficiency materials will have to be managed. We observe that burn in degradation is caused by light induced traps but shows different characteristics in amorphous and crystalline polymers. While in PCDTBT, which is mainly amorphous, fast Voc losses are observed, they are absent in crystalline P3HT. We show that KP115 is another highly crystalline polymer with only negligible Voc losses during burn in. We distinguish bulk degradation from interface

degradation by replacing the metal electrodes on aged devices. This allows us to identify light induced traps in the bulk and show a direct correlation between those traps and open circuit losses in amorphous materials.

With transient photocurrent techniques we observe the formation of light induced traps in several amorphous and crystalline polymers. All polymers show an increased trap density after aging, but only amorphous materials lose Voc, solar cells from highly crystalline materials don't show characteristic performance losses. We propose a reduced activity of traps in crystalline materials due to spatial separation of electrons and holes. Recent work of several groups on the three phase morphology has shown an energetic driving force for charge carriers to leave mixed regions and travel in pure phases. The absence of recombination partners in pure phases seems to make crystalline materials intrinsically more stable against trap assisted recombination through light induced localized states.

9184-403, Session Plen

Charge and Spin Transport Physics of Organic Semiconductors

Henning Sirringhaus, Cavendish Lab., Univ. of Cambridge (United Kingdom)

Over recent years there has been tremendous progress in discovering new organic semiconductors that provide high charge carrier mobilities for both n-type and p-type device operation, good operational stability and other functionalities such as efficient electroluminescene, sensing or memory functions. These materials allow addressing an increasingly broad range of flexible and printed electronic applications based on controlled manufacturing of flexible plastic substrates by a combination of solution processing and direct printing. One of the sources of improvement in performance has been the versatility of organic chemistry to provide a broad range of new molecular structures and the ability to assemble these molecules into ordered structure with minimum degree of disorder. We will review recent insights into the device and charge transport physics of solution-processible small molecule as well as conjugated polymer organic semiconductors, with a particular focus on the microscopic processes that limit the field-effect mobility in these systems. We are also interested in understanding the spin transport physics of these materials and the relationship between molecular structure, microstructure and spin diffusion. Organic semiconductors may enable realisation of long spin relaxation times and long spin diffusion lengths due to the weak spin-orbit coupling in these carbon-based materials. We will present recent measurements of spin-transport in different molecular and polymeric semiconductors.

9184-21, Session 6

Highly efficient perovskite solar cells by a low temperature solution process and its working principle *(Invited Paper)*

Jinsong Huang, Univ. of Nebraska-Lincoln (United States)

Low temperature solution processes are particularly attractive in the fabrication of large area devices such as solar cells to reduce cost. When it comes to organometal trihalide perovskites, which are a new generation of most attractive photovoltaic materials, it is challenging to form pinhole-free perovskite thin films by solution process. Here we show that continuous perovskite films were formed by the interdiffusion of the solution-deposited PbI_2 and CH_3NH_3I stacking precursor layers. It forms much better quality films with a ten-fold longer charge carrier diffusion length than those fabricated by existing methods, suggesting a new path to match charge diffusion length with the optical absorption length. The pinhole-free perovskite films have negligible leakage-current and large shunt resistance, resulting large fill factors close to 80%. A high efficiency of 15-17% was achieved in devices with perovskite/fullerene double layer architectures fabricated at temperature below 105 ºC. 85% of the optimized devices have efficiency above 14%.

The working mechanism of the interdiffusion-formed perovskite solar cell will be discussed in terms of charge trap formation and passivation, junction formation and electrode selection, and the origin of open circuit voltage.

9184-22, Session 6

Sub 150 °C processed meso-superstructured perovskite solar cells with enhanced efficiency

Konrad Wojciechowski, Michael Saliba, Tomas Leijtens, Antonio Abate, Henry J. Snaith, Univ. of Oxford (United Kingdom)

Recent rapid development of organolead trihalide perovskite-based solar cells opens an attractive route to the realization of a much cheap alternative to today's commercially available solar technologies. The ultimate lowest cost and most versatile method of manufacture should be solution based low temperature processing. The low temperature aspect enables a broad range of substrates to be used for the solar cells, with potential applications ranging from space to light weight portable power with form factor, in addition to high throughput manufacture. Perovskite semiconductors are a perfect candidate to fulfil these needs thanks to their low cost, solution-processability and excellent optoelectronic properties. Until now however, the most efficient solar cells have employed 500 ºC sintered TiO_2 compact layers as charge selective contacts. Here, we have developed a low temperature processing route to compact TiO_2 films, which surpass the properties and subsequent performance in the perovskite solar cells, in comparison to the previous high temperature processed material. With our optimized formulation we demonstrate full sun solar power conversion efficiencies exceeding 16% in an all low temperature processed solar cell.

9184-23, Session 6

High efficiency dye solar cell *(Invited Paper)*

Fabrizio Giordano, Chenyi Yi, Joël Teuscher, Shaik M. Zakeeruddin, Michael Grätzel, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Dye Sensitized Solar Cells (DSSC) represents a reliable technology, ready for the market and able to undermine silicon solar cells for specific fields of application. Recently our group has reached the record efficiency (for liquid DSSC) of 13%, using a novel porphyrin dye coded SM315 in conjunction with cobalt redox electrolyte (1). This remarkable result has been achieved by judicious molecular modifications of the standard YD2-o-C8 porphyrin sensitizer. In particular, 4-(2,4-dihexoxyphenyl)-phenyl is introduced as the aryl group of the diaryl amine donor of the YD2-o-C8 and benzothiadiazole is incorporated in the acceptor part of the molecule. In general the DSSC device performance depends on the combination of dye/electrolyte. In cobalt redox electrolytes the bigger size of the cobalt complexes hampers its percolation through the meso-porous TiO_2 network thus wakening the regeneration circuit, implemented from the redox couple. In the case of porphyrin dyes based devices the mass transport problem is evident with cobalt based redox electrolytes due to the large size of the sensitizing molecule and bulky cobalt complex.

Herein we report a systematic study on various porphyrin sensitizers with structural differences and their influence on the DSSC performance with cobalt based redox electrolyte. We used a series of novel dyes based on structural modifications of the Dye coded Y350 (2). With these dyes the power conversion efficiencies reached over 12% under AM 1.5 G illumination (1000 Wm^{-2}). The effect of electrolyte additives, electrolyte solvent and photo-anode treatments on the device performance, is investigated by electrical, impedance spectroscopy, electrochemical and optical characterization studies. The dye regeneration efficiencies are measured by Transient Absorption Spectroscopy and correlated to the device photovoltaic parameters.

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9184-24, Session 6

Sn halide based perovskite sensitized solar cells covering up to 1060 nm

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All-solid state solar cells consisting of perovskite have recently attracted interest because of the high efficiency reaching 12-16%. We have also reported Pb perovskite solar cells with 13 % efficiency which was brought about by passivating porous titania surface with Y2O3 or aminoacid HI salts. However, the wavelength edge of light harvesting for the Pb perovskite has been limited to 800 nm. Light harvesting in the area longer than 800 nm (near infrared region: NIR region) is necessary to realize high efficiency tandem perovskite solar cells. It has been reported that some Sn halide perovskites have absorption up to 1000nm. However, there is no report on the Sn based solar cells. We have succeeded in harvesting energy in the NIR region by using Sn halide based perovskite materials. Conduction bands of Sn based perovskite was -3.9 from the vacuum level, which was shallower than that of titania (-0.40 eV) suggesting that electron injections are possible from these perovskites to titania. The cell has the following composition: F-doped SnO2 layered glass/compact titania layer/porous titania layer/Sn based perovskite material/ p-type polymer semiconductor. The edge of the incident photon to current efficiency (IPCE) edge reached 1040 nm. 4.18 % efficiency with open circuit efficiency (Voc):0.42 V, fill factor (FF): 0.5, short circuit current (Jsc): 20.04 mA/cm2 is reported.

9184-25, Session 6

P-contact metal oxide in efficient organometal halide perovskite/fullerene hybrid solar cells

Tzung-Fang Guo, Peter Chen, Kuo-Chin Wang, Jun-Yuan Jeng, Po-Shen Shen, Kuo-Cheng Chen, National Cheng Kung Univ. (Taiwan); Tsung-Yu Chiang, National Chung Cheng Univ. (Taiwan); Pei-Ying Lin, National Cheng Kung Univ. (Taiwan)

The application of metal oxide as the p-contact to fabricate the decent perovskite-based photovoltaics has been successfully reported in this work. The p-contact metal oxide exhibits several optical, electrical, and chemical advantages being the potential electrode-interlayer. A respectful solar to electrical PCE of 7.8% with a VOC = 0.92 V, a JSC = 12.43 mA/cm2, and a FF = 0.68 has been achieved with the device configuration of the glass/ITO/NiOx/CH3NH3PbI3 perovskite/PCBM/BCP/Al structure under standard 1 sun AM 1.5G simulated solar irradiation. In addition, the device composed of the mesoscopic nanocrystalline NiO/peroskite/PCBM configuration exhibits a VOC = 1.04 V, a JSC = 13.24 mA/cm2, and a FF = 0.69, corresponding to a higher magnitude of PCE to 9.51%. To the best of our knowledge, this is the highest magnitude of PCE for perovskite-based solar cells applying p-contact metal oxide. NiO electrode-interlayer is a p-type semiconductor of high work function of 5.4 eV, which is close to the valence band edge level of CH3NH3PbI3 perovskite (5.4 eV). The alignment of energy level minimizes the interfacial energy losses for the hole transfer and optimizes the photovoltage output of device. The efficient hole transfer at perovskite/NiO heterojunction was verified by photo-induced absorption spectroscopy, showing a broad spectral feature above 800 nm, the long-lived charge-separation state of NiO+/P-. The success of this new style device configuration of p-type metal oxide material has the advantages of providing robust perovskite-based thin film solar cells in future.

9184-26, Session 7

Highly-efficient inverted polymer solar cells based on a cross-linkable water-/alcohol-soluble conjugated polymer interlayer

He Yan, Hong Kong Univ. of Science and Technology (Hong Kong, China)

A cross-linkable water/alcohol soluble conjugated polymer (WSCP) material poly[9,9-bis(6'-(N,N-diethylamino)propyl)-fluorene-alt-9,9-bis(3-ethyl(oxetane-3-ethyloxy)-hexyl) fluorene] (PFN-OX) was designed. The cross-linkable nature of PFN-OX is good for fabricating inverted polymer solar cells (PSCs) with well-defined interface and to investigate the detailed working mechanism of high-efficiency inverted PSCs based on poly[4,8-bis(2-ethylhexyloxyl)benzo[1,2-b:4,5-b']dithio-phene-2,6-diyl-alt-ethylhexyl-3-fluorothithieno[3,4-b]thiophene-2-carboxylate-4,6-diyl] (PTB7) and (6,6)-phenyl-C71-butyric acid methyl ester (PC71BM) blend active layer. The detailed working mechanism of WSCP materials in high-efficiency PSCs were studied and can be summarized into the following three effects: a) PFN-OX tunes cathode work function to enhance open-circuit voltage (Voc); b) PFN-OX dopes PC71BM at interface to facilitate electron extraction; and c) PFN-OX extracts electrons and blocks holes to enhance fill factor (FF). Based on this understanding, the hole-blocking function of the PFN-OX interlayer was further improved with addition of a ZnO layer between ITO and PFN-OX, which led to inverted PSCs with a power conversion efficiency of 9.28% and fill factor high up to 74.4%.

9184-27, Session 7

Influence of fluorination and molecular weight on the morphology and performance of PTB7:PC71BM solar cells

Christopher R. McNeill, Monash Univ. (Australia); Xioaxi He, Univ. of Cambridge (United Kingdom); Subhrangsu Mukherjee, North Carolina State Univ. (United States); Scott E. Watkins, Tianshi Qin, Ming Chen, Commonwealth Scientific and Industrial Research Organisation (Australia); Lars Thomsen, Australian Synchrotron (Australia); Harald W. Ade, North Carolina State Univ. (United States)

The device performance and microstructure of a series of PTB7-based polymers with varied molecular weight and degree of fluorination are investigated. Although the energy level of the highest occupied molecular orbital is found to increase with degree of fluorination, a strong molecular weight dependence of device performance dominates any underlying fluorination-dependent trend on overall performance. Microstructural investigation using a combination of X-ray techniques reveals a striking effect of polymer molecular characteristics on film morphology, with the size of PC71BM domains systematically decreasing with increasing polymer molecular weight. Furthermore, the relative purity of the mixed PTB7:PC71BM domain is found to systematically decrease with increasing molecular weight. Comparing domain sizes with and without the use of the solvent additive diiodooctane (DIO), the effectiveness of DIO in reducing PC71BM domain sizes is also found to be strongly dependent on the molecular weight of the polymer. It is found that molecular weights of at least 150 kg/mol are required for DIO to be effective in reducing the PC71BM domain size in order to produce high short-circuit current densities. Finally, it is shown that relatively high device efficiencies can be achieved with low degrees of fluorination, with an efficiency of 4.6% achieved for a degree of fluorination of only 5.3%.

9184-28, Session 7

Improving spectral response in polymer-fullerene bulk heterojunction solar cells *(Invited Paper)*

Barry C. Thompson, The Univ. of Southern California (United States)

While the efficiency of bulk heterojunction polymer solar cells increases beyond 9%, it is still clear that there is much room for improvement in efficiency, lifetime, and cost-effective synthetic and fabrication approaches. We are investigating ternary blend solar cells based on two donor components and one acceptor component (or one donor and two acceptors), which have been recognized as a potential route to increase the absorption breadth of a solar cell and consequently the short-circuit current density. Recently, using a three-component system, we demonstrated for the first time that the open-circuit voltage of ternary blend solar cells is composition dependent and can be tuned across the full range defined by the corresponding limiting binary blends without negatively impacting the fill factor or the short circuit current. As a result, with judicious choice of components, the attainable product of short circuit current and open circuit voltage (and by extension the efficiency) in a single-layer ternary blend solar cell could be higher than is achievable with a standard binary blend solar cell. We have successfully demonstrated higher efficiencies in ternary blends based on two donor polymers and one fullerene acceptor than could be achieved in either of the limiting binary blends. Efforts toward developing a deeper understanding of the mechanism of operation in these ternary blends will also be discussed.

9184-29, Session 7

Elucidating double aggregation mechanisms in diketopyrrolopyrrole-based narrow bandgap polymer solar cells

Gang Li, Jing Gao, Univ. of California, Los Angeles (United States); Wei Chen, Argonne National Lab. (United States); Yang Yang, Univ. of California, Los Angeles (United States)

Narrow band gap polymer materials with photo response extended to infrared region are critical for recent technical breakthrough.In this talk, we will present of morphology control mechanism in a promising polymer - poly{2,6'?-4,8-di(5-ethylhexylthienyl)benzo[1,2-b;3,4-b]dithiophene-alt-5-dibutyloctyl-3,6-bis(5-bromothiophen-2-yl)pyrrolo[3,4-c]pyrrole-1,4-dione} (PBDTP-DPP). We reported organic solar cells based on the thin film composed of PBDTP-DPP as donor and PC71BM as acceptor, where (1,8-diiodoctane) (DIO) and DCB (CF-DCB) were shown to be two effective additive to CF solvent (CF-DIO & CF-DCB), achieving a PCE of up to 6.6%. We first show device evidence of the different morphology optimization mechanisms. Then detailed morphology study will be presented to elucidate the two different processes - transmission electronic microscopy (TEM), UV-visible absorption and grazing incidence wide-angle X-Ray ray Diffraction scattering (GIWAXS) for thin film characterization; and were studied with small angle neutron scattering (SANS) and UV-visible absorption for polymer solution characterization. Our results provide clear evidences for two different morphology optimization mechanisms in these two solvent mixture systems, both involving double aggregation processes – solution stage and solvent removing stage. While the solution to film transition shows similar crystallization process in both systems, the solution stage aggregation is very different. SANS and UV-vis absorption spectrum indicate relatively amorphous polymer aggregates are formed in the CF-DIO solution, while more crystalline polymer aggregates are formed in CF-DCB solution.

9184-30, Session 7

Characterizing energy level shifts between the pure and mixed regions in bulk heterojunction polymer:fullerene solar cells

Sean Sweetnam, Stanford Univ. (United States); Guy O. Ngongang Ndjawa, Kenneth R. Graham, King Abdullah Univ. of Science and Technology (Saudi Arabia); Jonathan A. Bartelt, Timothy M. Burke, Stanford Univ. (United States); Aram Amassian, King Abdullah Univ. of Science and Technology (Saudi Arabia); Michael D. McGehee, Stanford Univ. (United States)

A new picture of the bulk heterojunction (BHJ) polymer solar cell morphology has emerged recently, which indicates that the BHJ is composed of at least three phases: a highly ordered polymer rich domain; a disordered domain of intimately mixed amorphous polymer and fullerene; and a fullerene rich domain. Recent theoretical and experimental work have indicated a connection between this "three-phase" morphology and charge transport in BHJ polymer solar cells by showing that offsets in the energy levels of carriers between BHJ domains may improve charge collection efficiencies.

In this work, we show that energetic offsets do exist in polymers and arise primarily due to two factors, (i) bandgap widening due to conjugation lengths changes, and (ii) interfacial dipoles formed between the polymer and acceptor. Using a combination of photoelectron spectroscopy and spectroelectrochemistry, we characterize the energy levels for holes in all phases of a semicrystalline polymer in a BHJ, accounting for both bandgap widening and interfacial dipoles. We find that in P3HT there is an energetic offset of 100 meV between the amorphous and crystalline polymer domains due to bandgap widening. We also find that the addition of PCBM to P3HT increases the energy levels of the amorphous polymer domain by 100 meV, suggesting that energy level shifts due to intermolecular interactions can be as large as those induced by intramolecular disorder. Thus to properly characterize the carrier energy levels across all domains, intramolecular and intermolecular effects must both be accounted for.

9184-50, Session PWed

Hybrid anode buffer layer MoO3/CuI to improve the performances of the organic solar cells based on triphenylamine used as donor of electrons

Mohammed Makha, Univ. d'Angers (France)

We investigate the effect of the anode buffer layer (ABL) onto the power conversion efficiency (PCE) of multi-heterojunction organic solar cells based on small molecules. The deposition of a CuI layer between the ITO anode and an original electron donor ED, the thienylenevinylene-triphenylamine functionalized, allows improving significantly the short circuit current and the fill factor, while it decreases the open circuit voltage. On the other hand, a MoO3 buffer layer increases the open circuit voltage but does not permit achieving high short circuit current and fill factor.

For OPV cells realization, the ITO coated glass substrate placed in the vacuum chamber (10-4 Pa). The layers were deposited onto the substrate by sublimation. The deposited layers are consequently ABL, ED, C60, bathocuproine BCP, Al. The fullerene was the electron-acceptor and BCP was used as cathode buffer layer CBL. The effective area of each cell was 0.10 cm2. The thin films thicknesses were estimated in situ using a quartz monitor after calibration. Finally, the cell arrangement was glass/ITO(100nm)/ABL/ED/C60 (40 nm)/BCP (9 nm)/Al(100 nm). For comparison some OPV cells without any ABL have been also studied. The characteristics of the photovoltaic cells were measured using a calibrated solar simulator (Oriel 300W) at 100 mW/cm2 light intensity adjusted with a reference cell (0.5 cm2 CIGS solar cell, calibrated at NREL, USA). In order to qualitatively determine the effect of the ABL on the bulk conductivity, we have investigated the J-V characteristics of hole-only devices with MoO3 and CuI ABL. These devices were grown using high work-function ABL. The hole only devices were fabricated by replacing the C60 and the BCP EBL with high work function MoO3, which is well known to be a hole injector (collector) and a blocking electron layer. Hole only devices have been made using the same ITO covered glass substrate than those used to grow OPV cells. After deposition of the ABL, a TTB film thick of 40 nm has been deposited. Then the organic film has been covered with MoO3 film thick of 7 nm. Finally aluminium has been used as top electrode. Globally the power conversion efficiency obtained with CuI as anode buffer layer is one and a half time that obtained with MoO3.Therefore, we show that the use of a double anode buffer layer MoO3/CuI allows doubling the power conversion efficiency of the cells, a power conversion efficiency of 2.5% being achieved. We assume the reason for this may be due to the dual function of MoO3 and CuI, since both of them were able to reduce the hole injection barrier compared with bare ITO, while CuI improves the organic film conductivity through an optimization of the order in the films and MoO3 prevents leakage current through the diode. The study of the ageing process is in good agreement with this description of the effect of the different anode buffer layer.

9184-51, Session PWed

Organic photovoltaic devices: challenges and prospects

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The solar PV sector has shown potential in the market with the quite popular crystalline and thin film solar technologies. Now Organic photovoltaics is a future technology of the sector with a huge potential as it is cheap and easy to process and thereby is likely to enlarge the usage of the solar energy in our global balance. Providing energy with a recyclable product produced on very low energy costs and without toxic substances, organic photovoltaic cell is a very sustainable technology. Till now the efficiencies of organic solar cells are below the ones exhibited by the inorganic solar cells, but some significant improvements have been made in last few years. The power conversion efficiency (PCE) has been increased by almost a factor of 10 approaching 10% in the last decade. However stability of OPVs is a limiting factor for their commercialization and still remains an essential challenge to be overcome. In this critical review, we present the limitations of the organic photovoltaic devices in terms of low efficiency and stability along with the new advancements in technology, such as the development of new inverted architecture, new acceptor donor contact layers, fully printed organic devices that have been developed to show this technology prospective avenues to sustainability, so that they can compete with their inorganic counterparts in the long run.

9184-52, Session PWed

Solution-processed parallel tandem polymer solar cells using silver nanowires as intermediate electrodes

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Tandem solar cells using different bandgap absorbers are effective architectures to improve the efficiency of organic photovoltaic devices. Over the past decade, series-connected tandem polymer solar cells (PSCs) have advanced rapidly due to the development of various charge recombination layers. In contrast, solution processing of parallel tandem cells has lagged far behind due to the great challenge in establishing an efficient interlayer which has to incorporate a highly conductive and transparent electrode.

Herein, we report for the first time all-solution fabrication of parallel tandem PSCs using silver nanowires (AgNWs) as intermediate charge collecting electrodes. Theoretically, we show that parallel-tandem PSCs are capable of achieving comparable efficiencies to the series-tandem counterparts over a much wider range of material combinations. We designed and constructed an efficient intermediate layer, based on which parallel-tandem devices using DPP:PC60BM and P3HT:PC60BM as photoactive layers for the two subcells were fabricated by solution-processing. Cross sectional HR-SEM shows that all the layers are resolved without interlayer mixing. J-V characteristics show that the two subcells have FFs of 56% and 59% which resulted in a high FF of 58% for the tandem device. Significantly, the measured short-circuit current density (Jsc) of the parallel tandem cell (13.6 mA/cm2) is exactly identical to the sum of the Jsc values of the two subcells, indicating no significant resistance loss within the parallel connection. The stability investigation of the as-fabricated devices (stored and measured in ambient atmosphere) shows the encouraging result that the parallel-tandem cell as well as the two subcells maintained more than 95% of its initial PCE after a period of 30 days.

9184-54, Session PWed

Critical issues in transport characterization on polymeric photovoltaic materials

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Two critical issues in transport measurement on polymeric photovoltaic (PV) materials and their bulk heterojunction blends will be discussed. First, we demonstrate that significant minority carrier injection can be present in a nominally unipolar device for transport measurement. For a hole-only device with a structure of anode/polymer(or blend)/Au, electrons were injected from the Au cathode. However, this kind of device structure is widely used for mobility extraction by fitting the J-V characteristics with the space-charge-limited current (SCLC) model. Such leakage of electron current violates the requirement of the SCLC leading to incorrect current signals for fitting and therefore inaccurate parameters are extracted. To tackle this problem, we employed a thin interlayer to prevent the electron leakage so that the transport parameters can be correctly extracted. Second, we focused on batch-to-batch variations of a commercially available amorphous PV polymer namely, PCDTBT. Significant variations in their transport behaviors and device performances were observed. Gel permeation chromatography on different batches revealed that they have different molecular weight distributions. In general, all distributions consisted of a high and a low molecular weight component with different ratios. This difference in molecular weight results in difference in power conversion efficiency (PCE). Charge transport properties of these polymers were evaluated. The mobilities were ranged from 1.6E-8cm2/Vs to 2.7E-5cm2/Vs which corresponds to the PCE ranged from 2.5% to 5.7% respectively. Detailed temperature dependence experiments were carried out on the polymers. We show that the presence of the low weight component leads to a significant reduction of hopping distances, and therefore reduced mobilities. This study should provide clear guidelines for controlling batch-to-batch variations of PV polymers for device application.

9184-56, Session PWed

The influence of thermal processing protocol upon the crystallization and photovoltaic performance of organometal trihalide perovskites

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Harnessing sunlight to generate photovoltaic electricity based on thin film solar cell technologies is crucial towards delivering green, sustainable energy at reduced materials and fabrication cost. Thin film hybrid solar cells using solution-processable materials such as semiconductor nanocrystals, organic polymers, or dye-sensitized solar cells have achieved so far 7-12% power conversion efficiencies (PCEs).

Organic-inorganic hybrid perovskites, previously investigated for field-effect transistors and light emitting applications, have emerged in recent years at the forefront of solution-processable and abundant thin-film photovoltaic technologies yielding PCEs over 15%.

One key aspect for the highest device performances reported to date is film uniformity and coverage of the perovskite film.

In this work, we utilized in situ grazing incidence wide-angle X-ray scattering (GISAXS) and scanning electron microscopy to study the thermally-induced morphological and crystalline development of methylammonium lead mixed halide perovskite films.

We investigated the photovoltaic device performance with mesosuperstructured and planar heterojunction architectures under different annealing conditions. We observed that a short rapid thermal annealing at 130C leads to the growth of large micron-sized textured perovskite domains in contrast to conventionally annealed devices at 100C. This improved short circuit currents and power conversion efficiencies up to 13.5% for planar heterojunction perovskite solar cells likely due to reduced surface recombination at the grain boundaries.

This work highlights the criticality of controlling the thin film crystallization mechanism of hybrid perovskite materials and offers a simple pathway for further enhancements in perovskite solar cells.

9184-57, Session PWed

Inverted polymer solar cells based on thin ZnO films grown by Mist chemical vapor deposition system

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Extensive investigations have been conducted in order to synthesis high quality Zinc oxide (ZnO) thin films for numerous applications. These methods are either expensive to make or results polycrystalline thin films with low optoelectronic properties. Here we demonstrate a simple and inexpensive method to grow high quality ZnO thin films by mist chemical vapor assisted depositing (Mist-CVD) system for inverted polymer solar cell (IPSC) application. The IPSC performance fabricated by Mist-CVD grown ZnO thin films were compared with ZnO layer synthesized by conventional Sol-gel method. Variations in IPSC performance on the growth temperature and thickness of the ZnO thin films were prominently demonstrated. The surface morphology of the ZnO films was investigated using scanning electron microscopy, atomic force microscopy and correlated with IPSC performance. The transmittance and crystalline quality of ZnO thin films was evaluated by transmission spectroscopy and X-ray diffraction, respectively. High performance IPSC can be fabricated using this simple and inexpensive method by synthesizing high quality thin ZnO films.

9184-58, Session PWed

Hybrid reduced graphene oxide-metal oxide solution processed election transport layers for high performance organic photovoltaics

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We report a new solution processed electron transport layer (ETL) based on hybrid composite of reduced graphene oxide/metal oxide (ZnO) for high performance organic photovoltaics (OPV) cells. The OPV devices were based on standard structures of Glass/ITO/PEDOT:PSS/Active layer/ETL/Al with the active layer as PCDTBT:PC70BM and PTB7:PC70BM respectively. In comparison to fabricated devices incorporating solution processed ZnO as ETL, the utilization of the RGO/ZnO leads to an improved short circuit current exceeding 12.5 mA/cm2 and 15.0 mA/cm2 for PCDTBT:PC70BM and PTB7:PC70BM system respectively. This is in comparison to the devices with the ZnO as ETL which facilitates short circuit currents of 11.5 mA/cm2 and 14.5 mA/cm2. The superior device performance for the RGO/ZnO incorporated devices with power conversion efficiencies approaching 6.7% and 7.5% for PCDTBT:PC70BM and PTB7:PC70BM systems indicate that the inclusion of reduced graphene oxide to metal oxides improves the electrical properties assisting in better charge extraction from the active layer and minimizing carrier recombination between the active layer and back electrode. This is mainly due to the 16% improvement in the conductivity of ZnO upon inclusion of RGO. We also demonstrate large area modules of 40cm2 in size incorporating the hybrid ETL. These demonstrate an efficiency of 2.7% and show 17% improvement compared to the reference module. The highly efficient performance observed with RGO/ZnO interlayer brings the organic photovoltaic technology one step closer towards fabricating an all-solution processed module.

9184-59, Session PWed

All-plastic organic photovoltaic cells with a photovoltaic dynamic range of five orders of magnitude

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We present all-plastic semitransparent organic photovoltaic devices based on vacuum-free film-transfer lamination processing of the photoactive layer, a blend of poly(3-hexylthiophene) and indene-C60-bisadduct, as well as the top poly(3,4-ethylenedioxythiophene):pol y(styrenesulfonate) electrode. Film-transfer lamination results in the misalignment of defects that may occur and propagate in additive spin-coating of polymeric films on top of each other. As a consequence, such photovoltaic devices contain a low density of defects and yield high shunt resistance values of 10^8 Ohm cm^2 with low reverse bias dark current. These devices can therefore operate when the light irradiance is varied over five orders of magnitude. The large dynamic range of such solar cells also allows the elucidation of a linear trend of the open-circuit voltage (VOC) as a function of the logarithm of light irradiance, in contrast to leaky devices where the VOC collapses to zero at low irradiance. In addition, a trend of initially increasing fill factor (FF) as a function of the logarithm of light irradiance is seen, which is followed by decreasing FF at high irradiance. This behavior is also explained in the context of the single-diode equivalent circuit model of solar cells. The high photovoltaic sensitivity of these devices at ultra-low irradiance, opens-up new applications where low power can harvested in low-light environments.

9184-61, Session PWed

Organic photovoltaic cells with stable top metal electrodes modified with polyethylenimine

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Highly efficient organic photovoltaic devices (OPV) often incorporate calcium top metal electrodes. Although the use of calcium leads to OPV that demonstrate high fill factor (FF) and open-circuit voltage (VOC) values, its air instability and the consequent reduction in device lifetime preclude such devices from commercialization. Additionally, the lower reflectance of calcium compared to aluminum and silver results in less photons being absorbed in the photoactive layer diminishing the short-circuit current density (JSC). OPV with a so-called inverted geometry avoid the use of calcium top electrodes but the development of OPV with a regular geometry that avoid calcium is not only scientifically relevant but could also enable novel OPV module geometries with improved performance.

Here, we show that deposition of a thin layer of the amine-containing non-conjugated polymer, ethoxylated polyethylenimine (PEIE), between the photoactive organic semiconductor layer and the top metal electrode (aluminum, silver, or gold) improves electron collection in polymeric organic solar cells as compared to reference devices not containing PEIE. As a result, efficient solar cells are demonstrated without the use of the highly reactive low?work function metal, calcium, as the electron-collecting top electrode, but instead with the aforementioned metal electrodes. Devices based on the photoactive blend of poly(3-hexylthiophene):indene-C60 bis-adduct (P3HT:ICBA) with structure ITO/poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS)/P3HT:ICBA/PEIE/Al demonstrate overall photovoltaic device performance comparable to devices containing calcium electron-collecting top electrodes, ITO/PEDOT:PSS/P3HT:ICBA/Ca/Al, with VOC of 775 ± 6 mV, JSC of 9.1 ± 0.5 mA cm^-2, FF of 0.65 ± 0.01, and power conversion efficiency of 4.6 ± 0.3%, averaged over 5 devices at 1 sun.

9184-62, Session PWed

Understanding charge transport in vacuum deposited Schottky organic solar cells with microsecond transient photocurrent measurements

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The best performing vacuum deposited organic solar cells (OSCs) in literature employ the Schottky junction architecture to reach power conversion efficiencies of over 8%. Schottky junction OSCs consist of a high work function anode adjacent to an active layer composed of a fullerene acceptor matrix doped with small concentrations of donor material. This device structure grants high open-circuit voltages due to band bending and high photocurrents due to fullerene aggregate absorption. Interestingly, the electron mobility in the Schottky OSC architecture is found to be several orders of magnitude higher than the hole mobility, and yet the OSC fill factors remain reasonably high despite these poor hole transport characteristics. In this work, we examine charge transport in Schottky junction OSCs in greater detail through the use of microsecond transient photocurrent experiments. We systematically compare the photovoltaic output parameters, external quantum efficiency spectra and transient photocurrent behavior of devices with various donor:acceptor mixing ratios and different mixed layer thicknesses. The photocurrent decay profiles following brief pulses of illumination elucidate the influence of charge trapping and recombination during sweep-out. Our results indicate that the Schottky junction architecture is well suited for donor materials with generally poor hole transport characteristics, but is perhaps not ideal for systems with more balanced charge transport. We also discuss how the choice of OSC architecture affects overall performance, especially with regards to the charge transport characteristics of the chosen donor and acceptor materials.

9184-63, Session PWed

Reducing the variability in performance of organic solar cells containing vacuum deposited MoOx extraction layers

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Reproducibility in efficiency and lifetime measurements of organic solar cells (OSCs) remains a significant concern, especially with the development of more complex and modern multi-layer device architectures. In this work, OSCs are studied for their efficiency and photo-stability as a function of the quality of their thermally evaporated MoO3 hole extraction layer (HEL). To this end, the characteristics of the MoO3 film are demonstrated to change with subsequent evaporation steps from the same source material. These variations have significant effects on polymer OSCs (p-OSCs) based on poly(3-hexylthiophene-2,5-diyl) (P3HT) and phenyl-C61-butyric acid methyl ester (PCBM), with an effective halving of the power conversion efficiency after only three MoO3 evaporation steps. In contrast, vacuum deposited small molecule OSCs (SM-OSCs) based on chloroindium phthalocyanine (ClInPc) and fullerene (C60) appear to be unaffected by the history of the MoO3 source material. SM-OSCs are instead shown to be prone to large changes in efficiency as a function of the lag time in between deposition of the MoO3 HEL and subsequent photo-active materials. The dramatic loss in performance with increasing lag time is proposed to be due to a reduction in the effective work function of the indium tin oxide/MoO3 contact. Increased lag time between these deposition steps is also demonstrated to decrease the SM-OSC photo-stability. The results thus emphasize subtleties in materials deposition processes that can have substantial effects on obtaining reproducible and scientifically relevant data.

9184-64, Session PWed

The pure and mixed halide organic-inorganic perovskite solar material

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The low-temperature solution processed organic-inorganic perovskite solar material has attracted the interest of many researchers. Gratzel et al. and Snaith et al., both using different chemical compositions – pure halide (CH3NH3PbI3) and mixed halide (CH3NH3PbI3-xClx) respectively – holds the current power conversion efficiency record of ~15%. Surprisingly, even with the mixed halide's diffusion length of ~1um exceeding the pure halide's diffusion length of ~100nm, the efficiencies are comparable. Through time-resolved optical measurements, we study the electron dynamics within these systems in order to understand why the different compositions have similar performance, but different carrier characteristics. Understandably, solar cell performance is also affected by how efficient is the charge injection into its extraction layers. By measuring the transient absorption spectrum of the perovskite films with different electron charge extraction layers, it will shed light on how the significant the quenching is depending on the underlying mesoporous matrix.

9184-65, Session PWed

Utilization of metallic coils for TCO-less cylindrical DSSC: investigation of photovoltaic performance under lower light intensities

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The introduction of dye-sensitized solar cells (DSSCs) to solar cells family has given cheap alternative for facile solar energy harvesting. In the case of DSSC, although their efficiency has not been reached to inorganic counter parts however, it has been accepted as an efficient entrant in photovoltaic industry having potentiality for indoor applications since they perform well under lower light intensities. Implementation of cylindrical device architecture along with removal of TCO component are expected to broaden the application potential range of DSSCs. TCO-less cylindrical architecture has benefits such as reduction in cost due to absence of TCO, efficient sealing of the cell and solar tracking throughout the day. Hence, we combined our novel titanium (Ti) coil based cylindrical DSSC with the parabolic concentrator to see its effectiveness under irradiated light at lower intensities (0.1mW/cm2 to 1mW/cm2). It has been found that diameter of the metal wire and their surface treatment strongly influences the observed photovoltaic performance. Electrochemical impedance spectroscopic investigations reveal better electrical contact between nanoporous TiO2 and working metallic coil electrodes reduces the recombination and hence, enhances solar cell performance. Upon simulated solar irradiation at AM 1.5 condition, this solar cell exhibits a photoconversion efficiency of 4.7%. Results show that rate of decrease in efficiency with the light intensity was more pronounced without reflector as compared to that in the presence of parabolic reflector. Effect of variation in distance of the solar cell from the base of the concentrator and light intensity was analyzed in detail.

9184-66, Session PWed

Nanobump assembly for plasmonic organic solar cells

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We demonstrate novel plasmonic organic solar cells (OSCs) by embedding a nanobump assembly (NBA) for harnessing more light with a simple fabrication process. The NBA consisted of precisely size-controlled Ag NPs generated by an aerosol process at atmospheric pressure, and thermally deposited molybdenum oxide (MoO3) layer, which follows the underlying nano structure of NPs. The complete isolation of Ag NPs using MoO3 suppressed negative electrical effects from metallic NPs in the OSCs, working as a recombination center or exciton quenching sites. The active layer, spin-coated from the polymer blend solution, had an undulated structure conformably covering the NBA structure. The NBA structure enhanced light absorption within an active layer arising from increased near-field in the vicinity of NBAs as well as the multi-reflection between the cathode and the nanobumped anode. In addition, the NBA-structured plasmonic OSCs showed stronger forward light scattering and higher ratio of scattering cross-section to absorption ratio, compared to that incorporating Ag NPs in the flat solution based buffer layer (eg. PEDOT:PSS). As a result, the combination of undulated active layer and Ag NBA structure led to 18% improvement in the power conversion efficiency. Therefore, the NBA plasmonic structure provides a reliable and efficient light harvesting in a broad range of wavelength, which consequently enhances the performance of organic solar cells.

9184-67, Session PWed

All-inkjet-printed solar cells

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The prospective use of direct-write printing techniques for the manufacture of organic photovoltaics has made them highly attractive. OPVs can revolutionize small-scale potable electronic applications by directly providing electric power to the systems. However, no route is available for monolithically integrating the energy-harvesting units into a system in which other components such as transistors, sensors or displays are already fabricated. Here, we demonstrate all-inkjet-printed organic solar cells with an average power conversion efficiency of 2 %. It is noteworthy that all the fabrication and measurement processes were carried out in ambient condition. We also achieved highly efficient printed solar cells (over 5%) with a simple 3-layer structure whose cathode was only made with a non-printing method. Our in-depth study on PCDTBT:PC70BM layers demonstrated that inkjet-printed blend layer exhibited similar nanoscale structure, molecular arrangement and excited state dynamics to its spin-coated counterparts. Our results show that inkjet-printing technology helps dispel the scepticism on organic solar cells by opening new opportunities to make cost-effective, eco-friendly and fully-integrated photovoltaic modules.

9184-68, Session PWed

Pyrrolidinone derivatives as processing additives for solution processed organic solar cells

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Processing additives are used in bulk heterojunction active material formulations for improving the molecular ordering and phase separation of the acceptor and donor materials. Despite the increasing interest in using them for their beneficial effect on the efficiency of organic solar cells, the identification and selection of these processing additives remain a question that is rarely addressed in the literature.

We developed a selection method to identify processing additives based on the solubility properties of the acceptor, the donor and the solvents. The solubility properties are assessed by the Hansen Solubility Parameters (HSPs) which quantify the three major types of interaction of organic compounds. The HSPs of several acceptor and donor materials are experimentally determined. They are then used to define a set of selection rules. When applied to the archetypical system based on poly(3-hexylthiophene) and phenyl-C61-butyric acid methyl ester, the selection rules were successful in identifying three novel processing additives. Photovoltaic tests showed that these additives are capable of increasing the solar cells efficiency by a factor of two in comparison to control devices. These preliminary results also suggest that this selection method can be extended to other acceptor:donor systems.

Also, the effects of these processing additives (with concentration varying from 0 to 4 vol%) on the crystallinity and on the charge carrier mobility were investigated. Using these results, we propose a mechanism that explains the effects of the processing additives on the bulk heterojunction formation during solution deposition.

9184-69, Session PWed

Charge dynamics in alkanedithiols-additives in P3HT:PCBM bulk heterojunction solar cells

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Addition of a small fraction of high boiling point solvent into the host of donor/acceptor blend is one the best approach to control the morphology to enhance the power conversion efficiency of organic bulk heterojunction (BHJ) photovoltaic devices. Herein, we focus on the role of different additives((a) 1,5-pentanedithiol (PDT), (b) 1,6-hexanedithiol (HDT) and (c) 1,8-octanedithiol (ODT)) in the performance of P3HT:PCBM photovoltaic devices and establish a relation with morphology and charge dynamics, studied by transient absorption spectroscopy (TAS). Grazing incidence X-ray diffractometry (GIXRD) and small angle x-ray scattering data reveals direct relation between additive's boiling points and induced phase separations. PCE as high as 2.9% is achieved by optimum nano-phase separation as a result of improved charge dissociation and transport. Transient absorption spectroscopy reveals the highest charge generation and polaron formation rate in thermally annealed film in contrast to the other films with solvent additives. Ultrafast decay

dynamics exhibits the comparable nongerminate recombination rate at the long ns-μs timescale for the all blend films. In addition, charge dynamics reveals that low boiling point solvent additive (PDT) induces higher geminate recombination which causes inferior performance of devices in spite of higher absorption and lower trap density. This lower trap density recombination (geminate recombination) is also confirmed by light intensity-dependent electrical measurements.

9184-70, Session PWed

Hydrogen bonding and noncovalent interaction can make crystalline high efficient polymer for polymer solar cell

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Organic photovoltaic devices (OPVC) that can be fabricated by simple processing techniques are under intense investigation in academic and industrial laboratories because of their potential for mass production of flexible and cost-effective devices. Recent drastic improvement of the power conversion efficiency (PCE) of polymer solar cells is mainly attributed to the synthesis of new materials. To achieve high PCE of OPVC need to rational design of photo-active materials that have high crystallinity. To improve crystallinity highly planar structure is required. By using hydrogen bonding and noncovalent interaction can make conformation lock of polymer back bone. Here we have designed different series of planar conjugated polymer by using hydrogen bonding H---F, H---O, H---N and noncovalent interaction such as O---S, N---S and S---F. In presence of F atom polymer intra and inter chain packing increase that improve the crystallinity. We have realized that to design high efficient crystalline polymer it will be a good choice to think about hydrogen bonding and noncovolent interaction.

9184-71, Session PWed

Highly planarized Ag nanowire and carbon nanotube composite electrodes for organic photovoltaics

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Organic photovoltaics (OPVs) offer potential as an alternative source of renewable energy. Whether OPVs can reach their potential of low cost factor, light weight and solution processable fabrication at low temperatures is dependent on all the materials that are incorporated into the device. Reported high efficiency organic photovoltaic cells are normally fabricated on indium tin oxide coated glass substrates. ITO on glass is brittle and poorly flexible, and the cost of ITO, increasing scarcity of indium and migration of the indium into the organic layer, provide strong motivation to develop alternate transparent conducting electrodes. Here we demonstrate a planarized nanocomposite electrode of interwoven Ag nanowires (AgNW) and single wall carbon nanotubes (SWCNT) with average transmittance of ~86% across the entire visible spectrum and sheet resistance < 10 ?/?. The work function of these electrodes is comparable to work function of ITO (~4.7 eV). We will report the OPV fabrication methods and the performance of the devices. Preliminary results of a device with the structure: Substrate/AgNW+SWCNT/MoOx/PCDTBT:PC71BM/Al have already shown an efficiency > 2%.

9184-72, Session PWed

Spectroscopic characterization of crystalline non-fullerene organic blends for solar cells

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Solar cells based on blends of conjugated polymers with fullerenes, such as PC61BM and PC71BM, have been intensively investigated but there are far fewer reports on blends that incorporate non-fullerene electron acceptors. One interesting feature of non-fullerene acceptors is that they typically have higher absorption coefficients than fullerenes and can therefore make a greater contribution to the photocurrent through photoexcited hole transfer to the polymer. Furthermore, they also present a broader platform on which to investigate the effects of blend microstructure on the photophysics of the system and ultimately device performance.

We report an investigation into the nature of photoexcitations in blends of varying ratio of P3HT with the small molecule electron acceptor K12[1] using photoinduced absorption (PIA) spectroscopy, photoluminescence quantum yield, steady-state and time-resolved photoluminescence measurements. K12 has a tendency to crystallize and the performance of devices incorporating blends with P3HT depends strongly on the blend ratio and processing conditions.[2] The results show that optimizing the microstructure requires a delicate balance between the crystallinity of the K12 and maximizing harvesting of the K12 singlet excitons. Furthermore, the results show that the natural tendency of the K12 to crystallize can cause the microstructure of the blend to evolve over time but that thermal annealing can be used to lock-in the optimum microstructure.

[1] P. E. Schwenn et al., Adv. Energy Mater. 2011, 1, 73–81.

[2] P. Wolfer et al., J. Mater. Chem. A 2013, 1, 5989.

9184-73, Session PWed

Towards efficient organic photovoltaic cells: enhancement of light trapping with breath figure patterns

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Polymer layers with self-assembled nanostructures have been proposed as an effective anti-reflective coatings for optical applications[1]. Porous structures in poly(methyl methacrylate) can be easily formed by deposition of the polymer solution in humid atmosphere[2]. Due to evaporative cooling during solution deposition droplets of water condense on the surface of polymer solution. These droplets sink into the solution and form so called breath figure patterns after complete drying. Porous structures formed this way are very uniform over a large area and can be used as broad-band anti-reflecting coatings for organic solar cells.

Using the method of creating breath figure patterns developed recently in our group [3] we have fabricated anti-reflective layers on the surface of polymer solar cells. By varying the relative humidity at the time of deposition and the water content of the polymer solution we have obtained structure of different sizes varying from 0.25 to 3 ?m as seen in topographic images acquired with Atomic Force Microscopy. Collected current-voltage characteristics indicate an increase of the photovoltaic performance only if pattern of anti-reflective coating was below 1 ?m. This is in accord with computer simulations performed.

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9184-74, Session PWed

The influence of SAM modification of PEDOT:PSS anode on the performance of organic solar cells

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Interactions at the internal and external interfaces affect self-organized structures of thin films of polymer blends. Studies on model systems have shown that modification of film substrate with self-assembled monolayer seems to be the most effective way to tune the interactions of blend components with confining surface.[1] On the other hand, nanostructure of thin films of conjugated macromolecules affects the overall performance of organic opto-electronic devices, especially polymer solar cells.[2] As it was shown the nanostructure depends on the blend composition, solvents used in the course of film casting, and parameters of post-fabrication annealing. Little work has been done to study the influence of the interactions with the substrate on the morphology of active layers of organic photovoltaic devices.[3, 4]

This work summarizes our recent studies on the effect of modification of poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT:PSS) with self-assembling molecules (SAM) on the morphology and electro-optical properties of thin films of polythiophene(PT): phenyl-C61-butyric acid methyl ester (PCBM) blends fabricated on top. Atomic Force Microscopy and Secondary Ion Mass Spectrometry gave an insight into the morphology of thin films. Current-voltage characteristics of PT:PCBM solar cells prepared on SAM modified PEDOT:PSS show that the performance of photovoltaic devices strongly depends on the type of molecule used.

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9184-76, Session PWed

Multiscale study of the effect of solvent on the glass transition temperature, molecule diffusion, and reorientation of P3HT-PCBM

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Exciton transport plays an important role in the overall exciton dissociation process and must be optimized to yield high efficient OPV device. In this contribution, the influence of solvents and the nanoscale phase separations they caused on the glass transition temperatures (Tg) of P3HT-PCBM mixture were studied by reverse mapping mesoscale simulation results back to the molecular dynamics. Glass transition temperatures of P3HT-PCBM at different mix ratio without solvent and with chloroform, dichlorobenzene, and chlorobenzene were obtained. Diffusion and reorientation ability of molecules and their subgroups at the temperature near Tg were also discussed.

9184-77, Session PWed

Holographic spectral beamsplitting for increased organic photovoltaic conversion efficiency

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Due to limitations in material absorption, organic photovoltaic cells often fail to collect light over the full solar spectrum, limiting power conversion efficiency of a single device. In this paper, two organic photovoltaic cells with complementary EQE curves are used in a spectrum splitting module to increase power output. The module utilizes a reflective hologram to split the incident beam into two spectral bands. Performance of the holographic spectrum splitting system is measured and evaluated in terms of Improvement over Best Bandgap (IoBB) of the two-cell combination. The spectrum splitting system achieves a measured power output and conversion efficiency which is higher than that of the best performing cell under the full spectrum.

9184-78, Session PWed

Degradation effects on charge carrier transport in P3HT:PCBM solar cells studied by Photo-CELIV and ToF

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Degradation Effects on Charge Carrier Transport in P3HT:PCBM Solar Cells Studied by Photo-CELIV

Research in the field of organic solar cells (OSC) is still in an exciting phase, with the number of scientific articles on the topic exponentially increasing over the past decade. However most of the focus so far has been on maximizing the efficiency whereas the equally important aspect of device stability has been given little attention.

In this communication, we investigate the irreversible degradation [1] in inverted organic solar cells based on poly(3-hexylthiophene) (P3HT): phenyl-C61-butyric acid methyl ester (PCBM) bulk heterojucntion active layer via photo-induced carrier extraction by linearly increasing voltage (Photo-CELIV) technique [2].

OSC devices have been degraded under controlled conditions and categorized according to percentage loss in optical density. From CELIV studies, we report an increase in concentration of equilibrium carriers while the density of photo-generated carriers is found to be decreasing with increasing degradation, in agreement with results obtained from optical measurements reported by Karuthedath et. al. [3]. Also, a reduction in the average mobilty of the blend is observed, as degradation proceeds. The increase in equilibruim carriers can be attributed to hole doping in the active layer as a result of increase in electron traps [4] whereas decrease in extractable photo-generated carriers and mobility could be attributed to deviations from ideal microstructural morphology with progressive degradation.

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9184-79, Session PWed

Increasing optical density of single-layer multi-polymer bulk-heterojunction OPVs using CdSe(ZnS) core(shell) quantum dots

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Photovoltaic technology has powerful implications from commercial and national security standpoints. Due to the high material cost of silicon solar devices, inexpensive and lightweight polymer based solar is desirable to meet the demand for decentralized electrical power production in traditionally “off-grid” areas. Using a blend of Poly(3-hexylthiophene-2,5-diyl) (P3HT), Phenyl-C61-butyric acid methyl ester (PCBM), and the low band-gap polymer Poly[2,6-(4,4-bis-(2-ethylhexyl)-4H-cyclopenta [2,1-b;3,4-b?]dithiophene)-alt-4,7(2,1,3-benzothiadiazole)] (PCPDTBT), we have fabricated devices with a wide spectral response and 3% power conversion efficiency in AM 1.5 conditions. Due to low absorptivity in the peak of the solar spectra (500 nm), we have blended this previous polymer system with CdSe(ZnS) core (shell) quantum dots to improve absorption, and thus power conversion efficiencies. Devices were prepared with quantum dots with peak absorbance at 560 nm and an emission wavelength of 577 nm, with concentrations ranging from 0% to 10% by weight. The relationship between quantum dot concentration and device performance is discussed, along with the impact of quantum dot concentration on thermal resistance to morphology changes.

9184-80, Session PWed

Performance improvement of dye-sensitized solar cells by surface patterning of FTO electrodes

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Patterned FTO electrodes for dye-sensitized solar cells (DSSCs) are fabricated by a facile wet etching method. The pattern depth can be controlled by altering etching time. FTO is thoroughly etched away when etching time is over 300s. Most DSSCs with patterned FTO electrodes exhibit both larger open-circuit voltage (Voc) and short-circuit photocurrent density (Jsc) as compared to the DSSC with unpatterned FTO electrode. The energy conversion efficiency of DSSC gradually increases with increasing etching time and achieves a highest value when etching time is 240s. Then it drops abruptly as etching duration is longer than 240s. This indicates that an optimum pattern depth approximately 190 nm is required to acquire the best DSSC performance. The improved performance can be mainly attributed to enhanced light harvesting and light scattering due to larger amount of TiO2 nanoparticles filled in the pattern and more dye adsorption. More contact between TiO2 nanoparticles and patterned FTO with larger surface area is also an advantage. The sheet resistance of FTO dramatically increases when etching time is over 240s, and this can explain why device efficiency starts to reduce. It has been revealed from Nyquist plots that the charge transfer impedance at the TiO2/dye/electrolyte interface apparently influences the magnitude of Jsc as well as device performance. Electron transfer becomes easier and a higher h is thereby obtained when a DSSC has a smaller interfacial impedance. This study has demonstrated that there is obvious improvement in DSSC performance by surface patterning of FTO electrodes. With an appropriate etching condition, the highest energy conversion efficiency of 6.76% can be achieved, which is around 17% higher than that of the DSSC with unpatterned FTO electrode.

9184-83, Session PWed

Influence of selenophene-thiophene phase separation on solar cell performance

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The rapid development of polymer solar cell technologies has lead to the implementation of multi-chromophore polymer structures, such as donor-acceptor, block, or statistical polymers that provide better energy-gap tuning ability or spectrum coverage, but also make controlling morphology more complicated. We compare the morphology and solar cell device performance of selenophene-thiophene copolymers that have the same degree of polymerization and composition, and differ only in their sequence (statistical vs. block copolymers). P3HS-b-P3HT spontaneously undergoes phase separation and P3HS-s-P3HT does not. P3HS-b-P3HT performs best when the intrinsic self-assembled nanostructure is the most perturbed. P3HS-s-P3HT does not undergo intrinsic phase separation, and vapor annealing can be used to optimize the polymer:fullerene morphology, where better nanostructure is well correlated with the best device. While the block structure provides the best stability, the statistical structure is a valuable method to balance the advantage of different monomers while precluding large-scale polymer self-assembly that is a strong intrinsic property of block structure.

9184-84, Session PWed

Efficient upscaling of organic solar cells and modules: influence of simulation model on precision in determining the optimal geometry

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Limited lateral conductivities of the photoactive materials used in thin film solar cells necessitate the use of semitransparent electrodes for current collection and lateral current transport. Due to the tradeoff between electrical conductivity and optical transmission, typical values for the sheet resistances of semitransparent electrodes deposited on glass amount to 10-20 W/sq. The power loss due to Joule heating [1] and the accompanying voltage drop caused by this sheet resistance [2] is increasing with cell length in current transport direction and thus defines an upper limit for practical solar cell lengths within monolithic modules.

In the several approaches existing for calculation of the power loss, the semitransparent electrode layer is either modeled as one collective resistance in series to the solar cell (One-Diode-Model) or as distributed resistance over the whole area of the solar cell (Micro-Diode-Model). We present a quantitative comparison between these two conceptions to investigate the direct influence on the optimal solar cell geometry and to discuss the capabilities as well as limitations of each model.

The computational studies presented here are based on the material systems P3HT (poly(3-hexylthiophene) and PCDTBT (poly[N - 9?-hepta-decanyl-2,7-carbazole- alt-5,5-(4?,7?-di-2-thienyl-2?,1?,3?-benzothiadiazole)] blended with phenyl- C60/C70-butyric-acid-methyl-ester) for the photoactive layer. In addition a set of different semitransparent conductive electrodes was considered: ITO (indium doped tin-oxide), either deposited on glass or on PET (polyethylene terephthalate) foil, and highly doped PEDOT:PSS (poly(ethylene-dioxy-thiophene):poly(styrene-sulfonic acid)). Distinct differences, increasingly important for increased sheet resistances of the electrode used, are revealed between these two models, yielding important implications for their respective size-dependent validities.

9184-86, Session PWed

Plasmon-exciton interaction studied in the near-field

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No abstract available

9184-87, Session PWed

Importance of mixed phases and optimum domain purity on the photovoltaic performance of high-efficiency solution-processed small-molecule BHJ solar cells

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Recently great success has been achieved in bulk hetero-junction (BHJ) solution-processed small molecule BHJ (SM BHJ) solar cells. However, despite their recent rapid rise in PCE, there have been few detailed investigations using advanced characterization techniques to link structure and morphology to device performance - a well-known strategy to further optimize the power conversion efficiency. Here we present an in-depth study on the morphology of OPVs based on two small molecule donors (p-DTS(FBTTh2)2) and X2. We reveal and quantify using Resonant Soft X-ray Scattering (RSoXS), for the first time, the hierarchical structure in these two promising SM BHJ systems. The median domain size was found to correlate well with the photogenerated current. Multipeak analysis indicates presence of molecule-rich/PCBM-rich macro-phase separation and nano-phase separation within molecule-rich domains. This was also confirmed from measurement of average molecular orientation at D/A interface. The nanoscale phase separations do not show any preferential orientation whereas larger phase separations were found to have a face-on orientation in agreement with our morphology model. The median size corresponding to population of macro-phase separation length scale was found to be approximately twice compared to corresponding nano-phase separation as measured by RSoXS. The polymer aggregate structure from GIWAXS was found to correspond to the RSoXS revealed nano-phase. These results take us to a morphology paradigm in which suitably mixed phase and percolation are critical in order to optimize performance within a given preparation protocol and counters prevailing assumptions of device operation that are based on two-phase, interconnected morphology.

9184-88, Session PWed

An efficient interconnection unit composed of electron-transporting layer/metal/p-doped hole transporting layer and its operation mechanism in tandem organic solar cells

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Organic photovoltaics (OPVs) have shown lower efficiency than inorganic solar cells. One of the reasons is the narrow absorption of the organic materials used as active layers in OPVs. Tandem organic photovoltaics (TOPVs) are a potential candidate to extend the absorption range of the solar spectrum in the devices.

Here, an efficient interconnection unit (ICU), consisting of an electron-transporting layer (ETL)/metal/p-doped hole-transporting layer (p-HTL) structure for TOPV cells is reported. The ICU satisfies all the requirements of optical transparency, low voltage loss and for functioning as an optical spacer. The variation of the short circuit current (JSC) and open circuit voltage (VOC) of the TOPV cells with increasing the thickness of the p-HTL in the ICU followed the theoretical predictions, proving that the ICU does not disturb the electrical characteristics of the TOPVs up to a p-HTL thickness of 100 nm with minimal VOC loss (~3%).

Also, the correlation of the electrical properties of the p-HTL in the ICU with the performance of TOPVs is reported by systematically varying the doping concentration of the p-HTL in the ICU. The VOC is significantly increased as the doping concentration of the p-HTL increases due to the reduction of the difference between the Fermi level and the highest occupied molecular orbital (HOMO) level of the p-HTL. The fill factor (FF) is also enhanced with increasing the doping concentration due to the enhancement of the conductivity in the p-HTL and efficient hole transport at the interface between Ag and p-HTL through the tunneling process.

9184-89, Session PWed

Polaron photogeneration in P3HT-PCBM bulk heterojunctions revealed by infrared photoinduced absorption spectroscopy

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The performance of bulk heterojunction (BHJ) solar cells depends strongly on the morphological properties of the polymer film, which can be controlled to a large degree by synthesis and processing methods. In particular, thermal annealing and process annealing by solvent additives have proven to lead to the greatest improvement of photovoltaic power conversion efficiency in typical donor-acceptor systems like poly(3,4-dihexyloxythiophene) P3HT and fullerene derivative PC60BM. This is reflected by the yield and spectral signatures of photogenerated polarons probed by the Infra-Red Active Vibrational (IRAV) modes as well as visible- to near-infrared polaron peaks in steady state and transient photoinduced absorption spectra. In this work we use density functional theory to assign IRAV and polaronic signatures to photogenerated charged states in P3HT/PCBM bulk heterojunction thin films, and perform a systematic study on the influence of preparation conditions on charge photogeneration and photovoltaic performance by broadband photoinduced absorption spectroscopy.

9184-90, Session PWed

Surface dependent nanostructures of ultra-thin copper(II) phthalocyanine films and their thermal evolution

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Control of the nanostructure and the surface morphology is an important issue in small molecular (SM) organic photovoltaics (OPVs), in order to improve the device performance with mixed donor–acceptor (DA) structures fabricated by the co-deposition of donor and acceptor materials.

Despite these interesting results related to the control of the nanostructure in SM OPVs, the initial nanostructures and their evolution during thermal annealing have not been reported to the best of our knowledge. Here we report the real time variation of copper(II)

phthalocyanine (CuPc) nanostructures during thermal annealing when grown on both hydrophilic and hydrophobic Si substrates. CuPc is good model system to investigate the molecular crystallinity and nanostructure because it is an archetype planar molecule which is extensively used in organic semiconductor devices such as OPVs, OFETs,8 and organic photodetectors. We focused on a 5 nm thick ultra-thin layer which can represent the interfacial property between the organic layer and the substrate in organic photovoltaic and semiconductor devices, and this thickness is also somewhat thinner than the critical thickness of mobility saturation.

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9184-91, Session PWed

Room-temperature solution-processed metal oxides for efficient hole transport layer of organic electronics

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Interfacial carrier transporting layers between the organic layer and electrodes play a very important role in designing efficient and stable organic solar cells (OSCs). Among various materials available, transition metal oxides (TMOs) have great potential owing to their wide range of energy level aligning capabilities.

While TMO layers are typically formed by high-temperature and sputtering processes, we report a new approach with the features of room-temperature, water-free and solution-based process for forming metal-oxide based hole transport layers (HTLs) for OSCs. We propose a one-step method to synthesize low-temperature solution-processed TMOs of molybdenum and vanadium oxide with oxygen vacancies as n-dopants.

By using our TMOs, power conversion efficiencies (PCEs) of 4.0% (vs. 3.7% for PEDOT:PSS control) in P3HT:PCBM and of 7.75% (vs. 7.24% for the PEDOT:PSS control) in PBDTTT-C-T:PCBM OSCs are reached [1]. We recently have achieved solution processed MoOx at room temperature [2]. Further improvement of the electrical properties of the room temperature MoOx film is achieved by incorporating Ag nanoparticles (NPs) to form Ag NP-MoOx composite film. Inverted PBDTTT-C-T:PCBM OSCs with PCE of 7.94% are achieved by using the Ag NP-MoOx composite film as HTL. Consequently, the solution-processed TMO HTLs can contribute to the further evolution of solution-process organic optoelectronics.

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9184-92, Session PWed

Direct measurements of hot CT states in isoindigo polymer systems for polymer bulk heterojunction solar cells by CMEAS

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Recent studies have shown that charge tranfer (CT) states in bulkheterojunciton (BHJ) organic solar cells (OSCs) not only determined the open circuit voltage (Voc) but also affect the short circuit current (Jsc) by mediating the exciton dissociation process. It has been shown that excitons in higher manifolds of CT states (or “Hot CT“ states) dissociate into polarons in tens of femtoseconds while the excitons in lower CT states (or “Cold CT“ states) result in CT recombination which is detrimental to the solar cell perfomance. Using charge modulated electroabsorption spectroscopy (CMEAS), we were able to directly measure the hot CT states in OSCs by monitoring the subtle changes of optical absorption in the sub-bandgap region induced by coupling of modulating field and the excitons generated by the sub-bandgap optical pumping.

In this report, two polymers p(iI-T) and p(iI-T3) is blended with PC71BM and CMEAS is performed to measure its hot CT posistion. While these two polymers appeared similar in terms of energy level measured by cyclic voltammetry and optical bandgap, the solar cell performance varied drastically in Voc (900 meV for p(iI-T) and 700 meV for p(iI-T3) and Jsc (2.5 mA/cm2 for p(iI-T) and 14.0 mA/cm2 for p(iI-T3)). The CMEAS result shows a significant difference in hot CT state energy resulting in different open-circuit voltages (1.27 eV for p(iI-T) and 0.97 eV for p(iI-T3)). Also, since the two polymers have similar HOMO and LUMO, more excitons in p(iI-T3) lies above hot CT threshold and have a higher probability of dissociation, leading to a higher Jsc.

9184-94, Session PWed

Charge transport in peptide nanostructures doped with MEH-PPV and carbazole derivatives

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Self-assembly of oligopeptides into distinct nanostructures is well known [1]. Among these diphenylalanine (FF) occupies a central role in the production of materials of scientific interest, due to its ability to self-assemble into highly ordered different nanostructures [2]. Nevertheless, the processes involved into the formation of these different nanostructures [1,2,3,4, 5] are not fully understood, and to understand them can lead to advances in several technological areas. These structures can also assemble to electroluminescent molecules and polymers, giving rise to interesting composites showing properties that are suitable for their use in photovoltaics.

In this study, combined the self-assembled FF nanostructures produced by distinct methods with MEHPPV and 9-vinyl carbazole as additives, using Tetrahydrofuran (THF) and water as solvents. The different materials obtained were imaged by scanning electron microscopy (SEM) and analyzed by fluorescence spectroscopy. Also, computational modeling was employed to inform on the interaction mechanisms and the electronic energy levels involved in the charge transfer complexes formed by these materials combinations. SEM images suggest that the additives and processing media strongly influence the final nanostructure, which is confirmed by fluorescence spectroscopy.

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9184-95, Session PWed

The origin of high open circuit voltage in organic-inorganic hybrid perovskite solar cells

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TThe perovskite solar cells, which are based on the organic-inorganic hybrid perovskite material CH3NH3PbI3, are featured with high open circuit voltage of about 1.0V. Our model simulation suggest that the large band gap energy of about 1.55 eV is not sufficient for producing the high open circuit voltage. However, after adding the reduction factor for the Langevin's bimolecular recombination rate in the continuity equations of charge carriers, the open circuit voltage is significantly improved and the fill factor is increased as well. By simulating the carrier distribution profile this reduced bimolecular recombination is explained as follows: since the exciton dissociation mainly occurs at the two interfaces with ultrafast dissociation rate, the electrons and holes are accumulated near the respective interface and diffuse toward the deep region of the absorbing layer. So a very steep carrier density gradient is formed inside the device, which may lead to a reduced bimolecular recombination rate compared with Langevin's theory. It is found that the distribution of the product of electron and hole density becomes flat gradually as this reduction factor reduces by orders of magnitude, giving rise to a true flat band or open circuit condition. So the reduced bimolecular recombination plays key role in producing high open circuit voltage. Further study shows that the large exciton diffusion length and the coexistence of exciton and free carrier excitation may also contribute to the high open circuit voltage to some extent.

9184-96, Session PWed

Benzothiadiazole or pyrimidine? Which is the promising acceptor moiety for D-A-A small molecule donor materials in organic solar cells? A theoretical evaluation

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During the past years, solar energy has been extensively studied among the renewable energy sources due to its clean, unlimited and readily available. Among all existing solar cells, organic solar cell (OSC) is one of the most promising technologies for the low cost energy production with the prominent merits of flexibility, thinness and simple manufacturing process. Nevertheless, the PCE of OSCs still lag behind that of the traditional silicon-based solar cells, which will retard their large-scale commercial application. As donor materials are the key component of OSC, materials optimization has become an effective way to improve the performance of these devices. A series of parameters determining the final efficiency of OSC were evaluated and deeply discussed using density functional theory and time-dependent density functional theory. The results shows that the system 2 with pyrimidine as the acceptor unit has a lower HOMO and lead to a larger Voc. while the larger driving force and dipole moment variation, the longer charge transfer distance, the more charge transferred, the red-shifted absorption spectrum and the slower charge recombination rate and comparable exciton dissociation rate in a molecular model of the donor/acceptor interface could lead to higher Jsc, highlighting the potential of pyrimidine as an acceptor unit in D-A-A donor materials.

9184-97, Session PWed

Designing high efficiency organic photovoltaics by controlling the ordering at the donor-acceptor interface

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Controlling and manipulating the charge transfer rate at the donor-acceptor interface is the essential key for achieving high efficiency organic solar cell (OSC). The overall power conversion efficiency in an organic solar cell depends on the balance between the rates of exciton dissociation, recombination and separation at the donor acceptor interface. Conventional bulk heterojunction solar cell architecture doesn't have a complete control over those rates at the interface. Here, we demostrated that we can manipulate the charge transfer rate at the P3HT/C60 interface by inserting a mono- and multi-layer of functionalized oligothoiphenes, which leads to a complete suppression in the exciplex (or charge transfer state) recombination. We observe that the photocurrent increases by 300 times, which in turn results in an increase in the overall power conversion efficiency from 0.03% to 0.3% in bilayer system. We incorporated oligomer in bulk-heterojunction device (P3HT:ICBA) and improved the power conversion efficiency from 4.3% to 7%. Moreover, we find that the oligothiophenes with an odd number of rings (ter and penta oligothiophene) exhibit a much higher increase in the photocurrent in comparison to the oligothiophene with an even number of rings (tetra oligothiphene). STM measurements reveal that the oligothiophene with odd and even number of rings differ in their ordering respectively, that has a big effect on the overall device performance. We also find that this ordering is highly dependent on the side functional groups in the oligothiophenes. The mechanism of photocurrent generation will be discussed and a simple transport model will be used to explain the change in the charge transfer and recombination rates and predict current-voltage curves.

9184-98, Session PWed

Photophysics and charge transfer in donor-acceptor triblock copolymer photovoltaic materials

Kyra N. Schwarz, David Jones, Trevor A. Smith, Kenneth P. Ghiggino, The Univ. of Melbourne (Australia)

Efficient conversion of solar energy to electricity in low-cost organic photovoltaic (OPV) devices requires the complex interplay between multiple processes and components over various length and time scales. Optimising device morphology to ensure efficient exciton diffusion and charge transport as well as ensuring efficient charge photogeneration is necessary to achieve optimum performance in new materials. The conjugated polymer electron donor PFM (poly(9,9-diocetylfluorene-co-bis-N,N'-(4-methylphenyl)-bis-N,N'-phenyl-1,4-phenylenediamine)) and electron acceptor F8BT (poly[(9,9-di-n-octylfluorenyl-2,7-diyl)-alt-(benzo[2,1,3]thiadiazol-4,8-diyl)), comprise the novel tri-block copolymer PFM-F8BT-PFM. Synthesised in-house, this copolymer is designed to phase separate on the 20-30 nm scale – a domain size ideal for maximising exciton collection at the donor-acceptor interface. Despite this optimisation of domain size, the photophysics of block copolymers at the donor-acceptor interface are not fully understood. Using steady-state and spectroscopic ultrafast characterisation including high repetition-rate transient absorption spectroscopy, the dynamics of charge and energy transfer of the component polymers and the triblock co-polymer itself are investigated. This provides insight into the energy relaxation pathways in these polymers following light absorption, and in turn revealing short time-scale dynamics at the donor-acceptor intramolecular interface, important for understanding and optimising charge photogeneration in such novel materials.

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9184-31, Session 8

Correlating domain purity with charge carrier mobility in bulk heterojunction polymer solar cells *(Invited Paper)*

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Binary and ternary blends of amorphous and semi-crystalline anthracene-containing poly(p-phenylene-ethynylene)-alt-poly(p-phenylene-vinylene) (PPE-PPV) copolymers (AnE-PVs) and [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) were investigated in thin films and polymer solar cells. By varying the composition ratio of amorphous and semi-crystalline polymers, a strong modulation of morphology was observed due to the fact that the semi-crystalline polymer phase separates, but the amorphous polymer intimately mixes with PCBM, consistently resulting in distinct changes of all photovoltaic parameters. For a detailed analysis of the underlying photophysics, charge generation and recombination processes were investigated by transient spectroscopy.

Furthermore it is demonstrated, that based on the solution preparation conditions the semi-crystalline copolymer can be controlled in its aggregation state. The aggregation obtained within the photoactive layer has a clear monotonic impact on solar cell parameters such as fill factor, photocurrent and photovoltage – in good agreement with fundamental understanding present within the field. In conclusion, the AnE-PV-copolymer system applied consitutes a useful model-system yielding general strategies and conclusions for improving polymer solar cell performance via morphology control.

9184-32, Session 8

Multi-phase separation and internal structures in OPV blends as revealed by soft X-ray scattering

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Over the past decade research efforts in organic photovoltaics (OPV) have led to power conversion efficiencies approach 10%. However, these values are still insufficient for real-world implementation for these devices due to the well-established fact that morphology of the active layer is a key parameter in tuning the performance. The key challenge for the OPV community has been the ability to provide concrete information about domain structure and composition fluctuations at sub-100nm length scale. Resonant soft X-ray scattering (R-SoXS) is now well-established as a tool to probe mesocopic phase separation in OPV blends. We have recently developed an analysis technique involving fitting of scattering profiles with log-normal distributions, corresponding to multi-length scale phase separations. This novel analysis method reveals phase separation in blends from 10 upto 1000 nm length scale, including molecular packing and ordering that usually only GIWAXS can reveal. The smallest structure revealed by R-SoXS consistently agreed with in-plane coherence length obtained from WAXS. Our results have shown that for a number of high-performing systems, ranging from polymer:fullerene (PDPP3T, PBDTTPD) to solution-processed small-molecule:fullerene systems (p-DTS(FBTTh2)2 and X2), there exists hierarchical structure with well-defined size ratio and anti-correlated composition variation between different length scales. This takes us to a morphology paradigm in which suitably mixed phase and percolation are critical for optimizing performance and counters prevailing assumptions of device operation that are based on two-phase, interconnected morphology. Our results also point out that hierarchical structures are very complex and delineation of an ideal hierarchical morphology requires significant additional research.

9184-33, Session 8

Interplay between ordering effects and solar cell performance in PBDTTPD polymers *(Invited Paper)*

Pierre M. Beaujuge, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Among Organic Electronics, solution-processable π-conjugated polymers are proving particularly promising in bulk-heterojunction (BHJ) solar cells with fullerene acceptors such as PCBM.[1] In the past few years, we have found that varying the size and branching of solubilizing side-chains in π-conjugated polymers impacts their self-assembling properties in thin-films. Beyond film-forming properties, nanoscale ordering in the active layer governs material and device performance. For example, in poly(benzo[1,2-b:4,5-b']dithiophene–thieno[3,4-c]pyrrole-4,6-dione) (PBDTTPD), side-chain substituents of various size and branching impart distinct molecular packing distances (i.e., π–π stacking and lamellar spacing),[2] varying degrees of nanostructural order in thin films,[2] and preferential backbone orientation relative to the device substrate (Fig.1).[3,4] While these structural variations seem to correlate with BHJ solar cell performance, with power conversion efficiencies ranging from 4% to 8.5%,[2,3,5] we believe that other contributing parameters – such as the local conformations between the polymer and the fullerene, and the domain distribution/composition across the BHJ (i.e., pure/mixed phases) – should also be taken into account.[6,7] Other discrete modifications of PBDTTPD's molecular structure affect polymer performance in BHJ solar cells with PCBM, and our recent developments emphasize how systematic structure-property relationship studies impact the design of efficient polymer donors for BHJ solar cell applications.[8-10]

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9184-34, Session 8

Quantification of nano- and meso-scale phase separation and relation to donor and acceptor quantum efficiency, Jsc, and FF in polymer:fullerene solar cells

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Complex three-phase morphologies including pure PCBM aggregates, pure polymer aggregates and a mixed phase, which is thought to consists of dispersed PCBM in mostly amorphous polymer, have been observed or inferred in several cases. The structure and importance of the mixed phase have not been fully exploited or understood. We reveal and quantify for the first time the hierarchical structure in a promising and high performance polymer:fullerene blend, which contains polymer-rich/PCBM-rich macro-phase separation and a nano-phase separation within the polymer-rich domains. The detailed structure-performance relationship is established by symmetrically manipulating two characteristic length scales (?) which correspond to the meso- and nano-phase separation, respectively, and the average composition variations (< c>) at these two length scales using six different solvents combination. Using resonant soft x-ray scattering, we find that the meso-phase separation length scale ?2 is roughly four times larger than nano-phase separation ?1. Also, anti-correlated composition variations are observed between the two-length scales of phase separation for the first time. Furthermore, we find that the internal structures of the polymer-rich phases are important for charge separation and charge transport and is intimately correlated with device performance and the partial quantum efficiency of the polymer and fullerene constituents. The total photocurrent generated from PCBM and polymer is considered separately and correlated with length scale of macro- and nano-phase structure. FF shows an interesting correlation with the average composition variations. Both very pure domains and impure domains are not favorable for FF due to either bimolecular recombination loss. The highest FF is achieved when the suitable mixed phase and the balanced composition variations of macro-phases and nano-phases separation are formed. This is counter to prevailing assumptions of device operation that are based on a two-phase, interconnected morphology. This work is thus an important elucidation of the device operation paradigm of real devices, where morphologies are more complex.

9184-35, Session 8

Large scale molecular dynamics simulations of chain conformation and morphology in high efficiency co-polymers for organic photovoltaics *(Invited Paper)*

Ross Larsen, Travis Kemper, National Renewable Energy Lab. (United States)

The rapid improvements in efficiency of organic photovoltaic (OPV) devices in recent years have been driven largely by changes in the molecular structure of active layer materials that are designed to optimize their optical and electronic properties so as to yield large photocurrents and open circuit voltages. It is clear, however, that device efficiencies can change dramatically with changes in molecular weight, incorporation of solvent additives, and other modifications to processing conditions. Hence, how the active layer molecules organize within a film can have a large effect on OPV operation. As an extension of our efforts to identify promising molecular structures with electronic structure calculations, we report on atomistic molecular dynamics simulations of structure and morphology of donor-acceptor copolymer films. To predict polymer backbone conformations correctly, the torsional potential along the backbone between neighboring fused-ring structures must be accurately parameterized and we describe new classical force fields we have parameterized based on high level electronic structure calculations at the MP2 level. Armed with these potentials, we have performed large scale (100,000+ atoms) classical molecular dynamics simulations of conjugated polymer films for several different high efficiency materials that have been described in the literature. We report on the packing and structure of both crystalline and amorphous phases and describe changes in film structure as solubilizing groups along the backbone are changed. The predictions are compared to experimental diffraction measurements of film structure and implications for OPV material design are discussed.

9184-36, Session 8

Vertical stratification in organic bulk heterojunction solar cells and its impacts on device performance

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During the fabrication process of organic photovoltaic (OPV) devices, the bulk heterojunction layer is deposited from a solution containing both electron donors (e.g. conjugated polymer) and electron acceptors (e.g. PCBM). Complex morphology evolution processes, e.g. lateral phase separation and vertical stratification, can occur during the solution casting process of thin mixed polymer films. The nanoscale morphology of these thin films in both lateral and vertical direction plays a critical role in determining the performance of organic photovoltaic devices

This presentation reports vertical stratification and device performance in bulk hetero-junction solar cells made of PC70BM and a series of conjugated copolymers. The effects of polymer chemical structure, hole transport layer (MoOx and PEDOT:PSS) and film deposition method (spin and spray casting) on the vertical stratification of PC71BM in the active layer were determined by neutron reflectivity. OPV devices are fabricated with those different vertical morphologies. The performances of these devices are correlated with the vertical morphology. In extreme case, a pure polymer layer can form at either the anode or cathode interface. The polymer layer at the anode increases the open circuit voltage and is beneficial to device performance. The polymer layer at the cathode interface increases charge recombination and is found to significantly reduce the open circuit voltage and device performance.

9184-37, Session 9

Organic solar cells: from lab to Roll2Roll production *(Invited Paper)*

Christian L. Uhrich, Heliatek GmbH (Germany)

Small molecule vacuum deposited solar cells can be flexible, semitransparent and can be deposited on various kinds of substrates. By using doped transport layers, one can easily stack two or more individual sub cells on each other. Utilizing thin film optics we achieve efficiencies of 12% up to now.

These qualities combined with a superior low light behavior and slightly positive temperature coefficient make organic solar cells an excellent product with a large design freedom.

We report about the latest results from our Lab and present strategies how to reach power conversion efficiencies of 15-17% in the near future. One important step in this direction is the development of new NIR Absorbers to harvest more light and to build more transparent solar cells.

Furthermore, we report about the production of pin tandem solar cells in our R2R machine and give an overview about Heliatek’s business development.

9184-38, Session 9

Organic nanoparticles to enable the environmentally friendly fabrication of organic solar cells fully from aqueous/alcoholic solutions

Stefan Gärtner, Karlsruher Institut für Technologie (Germany); Marco Christmann, Bernd Baumstümmler, MJR PharmJet GmbH (Germany); Eva-Marie Prinz, MJR PharmJet GmbH (Germany) and Karlsruher Institut für Technologie (Germany); Bernd Penth, Synthesechemie Dr. Penth GmbH (Germany); Alexander Colsmann, Karlsruher Institut für Technologie (Germany)

Despite the remarkable power conversion efficiencies of more than 10%, the industrial fabrication of organic solar cells is often hampered by toxic solvents that require strong safety precautions. Whereas the use of chlorinated solvents or toxic hydrocarbons is feasible in the lab, their use in large scale printing processes would lead to enormous operational costs, which conflicts with the goal of cost effective production. In this work, we fabricate organic solar cells entirely from aqueous and alcoholic solvents. For the absorber layer, we disperse, investigate and use P3HT:ICBA nanoparticles in environmentally friendly dispersion agents such as ethanol. For the preparation of the dispersions, we intentionally omitted any stabilizers that otherwise remain in the active layer, negatively affecting the device performance. In an inverted solar cell architecture with a nanoparticulate P3HT:ICBA layer the power conversion efficiency nearly matches the performance of reference devices that were fabricated from dichlorobenzene. Atomic force microscope investigations of the P3HT:ICBA surface reveal homogenous layers. The universality of this approach allows the use of other common organic photo active materials for the fabrication of solution processable organic solar cells from non-hazardous solvents.

9184-39, Session 9

Highly efficient multi junction organic solar cells with DCV2-5T-Me(3,3) as absorber material

Rico Meerheim, Christian Körner, Karl Leo, Technische Univ. Dresden (Germany)

The power conversion efficiency of organic solar cells can be increased by the use of the multi junction concept consisting of several serial stacked sub-cells. Ideally, the sub-cells contain spectrally complementary absorber materials to harvest sun photons over a wide spectral range. However, also with the same absorber material in the sub-cells an increased cell performance can be reached.

We present completely vacuum deposited and highly efficient multi junction organic solar cells with the absorber material DCV2-5T-Me(3,3) in all sub-cells and doped transport layers for a lossless charge transport in between. The absorber forms as donor in a C60 acceptor highly efficient bulk hetero junctions due to strong absorption, efficient charge separation and transport properties, and high voltages.

The layer thicknesses of the multi junction architectures were optically optimized for maximum cell efficiency by a transfer matrix algorithm, confirmed by experiments. The measurement of the external quantum efficiency under appropriate monochromatic light bias illumination allows the resolution of the spectral response of the sub-cells, even for multi stacks with the same absorber. The measured sub-cell EQE, according to the simulation, are spectrally shifted due to the micro cavity which forms a broadband response of the stacked cells. The nearly matched sub-cell currents in the optimized multi stacks increases the power conversion efficiency from 7,7% for a single junction up to 9% for a triple junction cell. The relative enhancement is even stronger for large area cells due to stronger influence of the ITO resistance which is important for OPV applications.

9184-40, Session 9

Solution processed flexible planar hybrid perovskite solar cells

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Organolead halide perovskites are attracting considerable attention due to their exceptional opto-electronic properties, such as high charge carrier mobilities, large exciton diffusion lengths, high extinction coefficients and broad-band absorption. These interesting properties have enabled their application in high performance hybrid photovoltaic devices. We report low temperature solution-processed flexible hybrid solar cells with CH3NH3PbI3-xClx, using [6,6]-Phenyl C61 butyric acid methyl ester (PCBM) and Poly[(9,9-di-n-octylfluorenyl-2,7-diyl)-alt-(benzo[2,1,3]thiadiazol-4,8-diyl)] (F8BT) as electron transport materials. The solar cells were fabricated on ITO coated PET sheets in a planar configuration of ITO/PEDOT:PSS/CH3NH3PbI3-xClx/PCBM(F8BT)/Al. PEDOT:PSS was employed as a hole transport material. Under standard AM 1.5G solar irradiation, these flexible solar cells yielded power conversion efficiencies of 6.47% and 4.69% with the electron transporting materials of F8BT and PCBM , respectively. The characterization of the materials, fabrication and evaluation of the hybrid solar cells will be reported.

9184-41, Session 9

In-situ transient absorption spectroscopy: a method for the characterization of roll-to-roll coated organic photovoltaic films

Jonathan M. Downing, National Institute of Standards and Technology (United States); Bob C. Schroeder, Iain McCulloch, Imperial College London (United Kingdom); Lee J. Richter, Dean M. DeLongchamp, David J. Gundlach, National Institute of Standards and Technology (United States)

In recent years the field of organic photovoltaics has increasingly looked to move past laboratory test cells and towards the creation of larger area devices. With this motivation, numerous groups have advanced from traditional film formation by spin coating to investigate blade coating, a method analogous to slot-die coating used in large area roll-to-roll printing. In operation, a blade is drawn across a substrate at a controllable height and speed to form a wet film. The subsequent drying conditions (time [1], solvent [2], additive concentration [3]) have been observed to be of key importance in the microstructural formation and final electrical and device performance.

Time resolved measurements allow drying to be observed with the ultimate goal of discerning optimal film morphology from processing conditions prior to device creation. Such measurements are conducted in-situ ¬ (during drying) and so operate without contact to the film. In this work, the technique transient absorption spectroscopy (TAS) has been applied to organic thin films to study drying. TAS probes the transient polaron population through optical excitation (pump) and IR-absorption (probe), quantifying the long lived free charge which is well correlated to device performance. The results of this experiment and associated electrical device measurements (IV-curves, transient photovoltage and CELIV) will be discussed to provide understand of the drying behaviours and correlate the morphology of P3HT:PCBM and GeIDT-BT:PCBM [4] thin films and devices.

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9184-42, Session 9

Flexible organic tandem solar cell modules: a story of up-scaling

George D. Spyropoulos, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Peter Kubis, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany) and Erlangen Graduate School in Advanced Optical Technologies (Germany); Ning Li, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Luca Lucera, Bayerisches Zentrum für Angewandte Energieforschung e.V. (Germany); Michael Salvador, Derya Baran, IMEET (Germany); Florian Machui, Tayebeh Ameri, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Monika M. Voigt, Bayerisches Zentrum für Angewandte Energieforschung e.V. (Germany) and Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Christoph J. Brabec, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany) and Bayerisches Zentrum für Angewandte Energieforschung e.V. (Germany)

The competition in the field of solar energy between Organic Photovoltaics (OPVs) and several Inorganic Photovoltaic technologies is continuously increasing to reach the ultimate purpose of energy supply from inexpensive and easily manufactured solar cell units. Solution-processed printing techniques on flexible substrates attach a tremendous opportunity to the OPVs for the accomplishment of low-cost and large area applications. Furthermore, tandem architectures came to boost up even more OPVs by increasing the photon-harvesting properties of the device.

In this work, we demonstrate for first time the complete realization road of a solution processed tandem flexible module from the origin of lab scale cell. Information exchange between device design, experimental optimizations and optical simulations lead to high efficient (PCE>7%) lab scale devices on glass. Subsequently, combinatorial material and printing engineering give birth to high performance (PCE>5%) flexible OPV Tandem devices. As a last experimental step, high performance flexible OPV tandem module devices with large active area (3500 mm2) utilizing ultrafast laser patterning are materialized and presented. The high resolution (<20microns) and high processing speeds (up to 4 m/s) give the module great geometrical fill factors and full compatibility with Roll to Roll production techniques. Finally, we enhance the concept of tandem solar cells by demonstrating that a maximum theoretical PCE value of 21 % for an organic tandem solar cell can be accomplished.

9184-43, Session 10

Stability of organic solar cells applying solution processed NiO hole transport layer: comparison with water-based V2O5 *(Invited Paper)*

Gerardo Teran-Escobar, CIN2 (Spain) and Consejo Superior de Investigaciones Científicas (Spain); Raphael K. Arfaoui, Institut Català de Nanotecnologia (Spain) and Consejo Superior de Investigaciones Científicas (Spain); Kion Norrman, Risø National Lab. (Denmark); Monica Lira-Cantu, CIN2 (Spain) and Consejo Superior de Investigaciones Científicas (Spain)

Transition metal oxides (TMOs) are good alternatives to organic buffer layers in Organic solar cells, OSCs. Their most attractive feature is the possibility to be fabricated by low temperature solution processing methods. TMOs exhibit a wide range of energy level alignments, good transparency as thin films, are easy to manipulate, and confer low-resistance ohmic contacts to the OSC. Moreover, TMOs can enhance the adhesion to the active layer and show higher stability to ambient atmosphere relative to the highly hygroscopic and acidic PEDOT:PSS. In his work we compare the outdoor stability of OSCs made with solution processing V2O5 and NiO hole transport layers (HTL). The devices show high stability in both cases with T80 maintained after 1000 h of testing. The initial burn-in process is completely different highly dependent on the HTL applied. IV curves, IPCE and TOF-SIMS analyses were used to understand the effect of the UV light on the photoactivation of the oxides and the interlayer mixing between the oxide and the organic active layer. This photoactivation strongly affects the V2O5 layer while the use of NiO resulted in much higher device stability and lifetime.

9184-44, Session 10

Solution processed interfacial materials for organic bulk heterojunction and planar heterojunction perovskite solar cells

Wei Lin Leong, A*STAR Institute of Materials Research and Engineering (Singapore); Natalia Yantara, Nanyang Technological Univ. (Singapore); Yi Ren, A*STAR Institute of Materials Research and Engineering (Singapore); Nripan Mathews, Nanyang Technological Univ. (Singapore)

The rapid development of organic bulk heterojunction as well as organometal trihalide perovskite solar cells necessitates the need for careful selection and optimization of the electrode interfacial layers within the solar cell for improved performance. In this work, we present the recent development of solution processed organic, inorganic and hybird interfacial materials for inverted organic bulk heterojunction and planar heterojunction perovskite solar cells. In particular, the mobility and carrier concentration in multi-component metal oxide (eg. indium zinc oxide; IZO) is tuned and their effect on photovoltaic performance in various types of light harvesting systems is studied. A study of photovoltaic performance in PTB7:PC70BM devices with IZO electron-transport layers of different stoichiometry compositions, will be presented. We have also incorporated IZO electron-transport layers in higher-performing perovskite based solar cells and investigated their electronic properties.

9184-45, Session 10

Semitransparent organic photovoltaic modules with Ag nanowire top electrodes

Fei Guo, Peter Kubis, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Thomas Przybilla, Erdmann Spiecker, Center for Nanoanalysis and Electron Microscopy (CENEM) (Germany); Karen Forberich, Christoph J. Brabec, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Semitransparent organic photovoltaic cells (OPV) have attracted growing interest in recent years which is mainly related to their specific applications for various (semi-)transparent architectures, such as windows, glass roof tops, curtain walls and integrated PV-chargers for portable electronics etc. An essential step towards commercialization of the OPV technology is the manufacturing of large-area modules with maximum power conversion efficiency close to the laboratory device level. Another critical issue that has to be addressed is the realization of solution-processability, by which the cost potential of this promising solar technology can be fulfilled.

In this presentation, we demonstrate, for the first time, solution-processed semitransparent polymer solar cell modules (ST-modules) based on ultra-fast laser patterning. In our ST-modules, with the exception of the bottom ITO-coated glass substrates, all layers including the top silver nanowire (AgNW) electrode were solution-processed via a doctor blading technique. The series inter-connection of the modules is realized by ultra-fast laser patterning. The efficient ohmic contact of the top AgNWs with the bottom ITO electrodes and high accuracy of the laser positioning enable the as-fabricated modules to show high electrical fill factor (FF) of 65% and extremely high geometric FF of >95%, respectively. Accordingly, our semitransparent modules show a PCE value of ~3.0% which is ~95% of the single cell reference with

active areas of 30 mm2. Besides, the fabricated ST-modules show a high transmittance of 50% at 550 nm, suggesting promising applications for semitransparent architectures.

Furthermore, we have also fabricated semitransparent modules on large-area flexible substrates and demonstrated efficient semitransparent double-junction OPV modules with solution-processed AgNW electrodes.

9184-47, Session 10

Plasmonic electrodes for organic photovoltaics: polarization-independent absorption enhancement

Beibei Zeng, Zakya H. Kafafi, Filbert J. Bartoli, Lehigh Univ. (United States)

Organic photovoltaics (OPVs) have achieved recently a power conversion efficiency (PCE) of 12%. Light trapping strategies are proposed to further increase the optical absorption in the active light-harvesting layer(s) without altering its (their) thickness(es) and consequently the short circuit current and PCE of the device. We systematically investigate the optical and electrical properties of ultrathin one- (1D) and two-dimensional (2D) Ag nanogratings (NGs), which are employed in place of ITO as plasmonic transparent conductive electrodes (TCEs) in molecular OPVs based on copper phthalocyanine (CuPc) and perylene tetracarboxylic bisbenzimidazole (PTCBI). Broadband and polarization-insensitive absorption enhancements have been achieved using these molecular active layers with either a single 2D Ag NG or two 1D Ag NGs sandwiching the active layers. A total photon absorption enhancement of 150% and 200% is estimated for the optimized 2D and double 1D Ag NGs, respectively. The mechanism for this absorption enhancement is attributed to the excitation of surface plasmon resonances and plasmonic cavity modes. Moreover, we demonstrate that the OPV device (Ag/active layers/Ag plasmonic cavity) functions as a perfect light absorber over the entire spectral region, as the incident angle increases up to 60 degrees.

9184-48, Session 10

Plasmonic-electrical effects and carrier accumulation effects of metal nanomaterials for high performance organic solar cells

Wallace C. H. Choy, The Univ. of Hong Kong (Hong Kong, China)

Optical and materials effects of plasmonic metal nanomaterials have been individually studied for enhancing performances of organic solar cells (OSCs). Differently, the effects of plasmonically induced carrier generation and enhanced carrier extraction of the carrier transport layer (i.e. plasmonic-electrical effects) in OSCs are quite interesting for comprehensive investigation. We demonstrate enhanced charge extraction in TiO_2 as an efficient electron transport layer by incorporating metal nanoparticles (NPs). While OSCs using pristine TiO_2 can only operate by UV activation, we observe efficient performance by using NP-incorporated TiO_2, at a plasmonic wavelength (560-600 nm) far longer than the UV light. By optimizing NP doping, performances of OSCs with various polymer active layers are enhanced and an optimal efficiency of 8.74% is reached [1]. From experimental and theoretical studies, we attribute the enhanced charge extraction under plasmonic illumination to the charge injection of plasmonically excited electrons from NPs into TiO_2.

Recently, we further report the TiO_2-metal NPs composite can enhance the carrier accumulation, which can fill the trap states and thus improve the electrical conduction of TiO_2 and the device performances [2].

Consequently, these work can contribute to new approaches and knowledge to utilize plasmonically electrical nanostructures in organic optoelectronic devices.

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9185-101, Session 1

The impact of isomeric purity on the performance of anthradithiophene-based transistors *(Invited Paper)*

John E. Anthony, Univ. of Kentucky (United States)

Solubilized anthradithiophene semiconductors are popular candidates for study in a variety of transistor configurations. However, they are always prepared as inseparable mixtures of syn and anti isomers. We have recently discovered a simple method to separate these isomers, and are now re-examining device performance from each separate isomer. We have prepared both fluorinated and hydrogen-terminated derivatives, and have studied the device performance in most configurations formerly studied with the isomeric mixture. We find that in certain cases, particular isomers do indeed show performance differences. The details and reasons behind these changes in performance will be discussed.

9185-102, Session 1

Naphthodithiophenediimide (NDTI): a new building block for versatile organic semiconductors *(Invited Paper)*

Kazuo Takimiya, Masahiro Nakano, Itaru Osaka, RIKEN (Japan)

In this contribution, we report on alpha,beta-unsubstituted naphtho[2,3-b:6,7-b']dithiophenediimides (NDTIs) in terms of the synthesis, electronic structure, crystal structure, and further applications to pi-extended semiconducting materials. Electrochemical and optical studies on N,N-alkylated NDTIs demonstrated that the compounds have a low-lying LUMO energy level (4.0 eV below the vacuum level) and a small HOMO-LUMO gap (ca. 2.1 eV), suitable as n-channel organic semiconductor. The NDTI unit can also be integrated into conjugated polymer backbone with various pi-building units to afford ambipolar or n-channel semiconducting polymers. In fact, NDTI-based small molecules can act active material for n-channel OFETs with mobility as high as 0.05 cm2/Vs. On the other hand, NDTI-based semiconducting polymers affords solution-processed n-channel OFETs and ambipolar transistors with relatively high mobilities. These interesting electronic properties testify that NDTI can be a promising and versatile building block for the development of novel pi-conjugated materials in future.

9185-103, Session 1

Bistetracene: an air stable, high-mobility organic semiconductor with extended conjugation *(Invited Paper)*

Alejandro L. Briseno, Lei Zhang, Univ. of Massachusetts Amherst (United States)

Herein we present the synthesis and characterization of "Bistetracene," an unconventional, linearly extended conjugation core with eight benzene units. The annellation mode of the system allows for increased stability of the conjugated system relative to linear analogues due to the increase number of aromatic Clar sextets. By attaching the appropriate solubilizing substituents, efficient molecular packing with large transfer integrals can be obtained. Charge carrier mobilities as large as 6.1 cm2 V-1s-1 and current on/off ratios of 107 are measured. Our study provides valuable insight into the design of unconventional semiconductor compounds based on higher polycyclic aromatic hydrocarbons (PAHs) for high performance devices.

9185-104, Session 1

Intertwined lamello-columnar co-assemblies in liquid-crystalline side-chain pi-conjugated polymers: towards a new class of nanostructured supramolecular organic semiconductors

Yiming Xiao, Danli Zeng, Univ. Pierre et Marie Curie (France); Martin Brinkmann, Institut Charles Sadron (France); Benoit Heinrich, Bertrand Donnio, Institut de Physique et Chimie des Matériaux de Strasbourg (France); Jeong-Weon Wu, Jean-Charles Ribierre, Ewha Womans Univ. (Korea, Republic of); Emmanuelle Lacaze, David Kreher, André-Jean Attias, Fabrice Mathevet, Univ. Pierre et Marie Curie (France)

The self-organization of pi-conjugated organic materials forming highly ordered supramolecular architectures has been extensively investigated in the last two decades in view of optoelectronic applications. Indeed, the control of both the mesoscopic and nanoscale organization within thin semiconducting films is the key issue for the improvement of charge transport properties and achievement of high charge carrier mobilities. These well-ordered materials are currently either self-organized semiconducting polymers or liquid crystals.

In this context, we endeavored to investigate the self-organization of side-chain liquid crystal (SCLC) semiconducting polymers where (i) the backbone is a pi-conjugated polymer and (ii) the side groups are pi-conjugated discotic mesogens.

Here we describe the design and synthesis of columnar side-chain liquid crystal homo and alternating (co)polymers with triphenylene mesogens as side groups, and well-defined regioregular polythiophene as backbone. These different kinds of architectures prepared following the Grignard methathesis (GRIM), allow the control of the triphenylene side group ratio along of the polymer chains, and lead to tunable electronic properties and nanostructures.

In this work, we will give the details on the synthesis, structural characterization and morphology studied by Polarized-light Optical Microscopy (POM), Differential Scanning Calorimetry (DSC), Temperature-dependent small-angle X-ray diffraction, Grazing-incidence X-ray scattering (GIXS) and Atomic Force Microscopy (AFM). Moreover, their charge transport properties studied in OFET configuration will also be depicted.

9185-105, Session 2

Polymers containing highly electroactive fused heterocycles for field effect transistors and single-material solar cell devices *(Invited Paper)*

Peter J. Skabara, Univ. of Strathclyde (United Kingdom)

Following an approach developed in our group to incorporate tetrathiafulvalene (TTF) units into conjugated polymeric systems, a low band gap polymer p(DPP-TTF) has been synthesised and characterised. This polymer is based on a fused thieno-TTF unit that enables the direct incorporation of the TTF unit into the polymer, and a second co-monomer based on the diketopyrrolopyrrole (DPP) molecule. These units represent a donor-acceptor copolymer system showing strong absorption in the UV-visible region of the spectrum. New, alternative electroactive units are demonstrated, possessing rigid sulphur/nitrogen heterocyclic units. For devices, an optimised p(DPP-TTF) polymer organic field effect transistor (OFET) and a single material organic solar cell (SMOC) device showed excellent performance with a hole mobility of 5.3 x 10-2 cm2/

Vs and a power conversion efficiency (PCE) of 0.46%, respectively. Bulk heterojunction organic photovoltaic (BHJ-OPV) devices of p(DPP-TTF) blended with phenyl-C70-butyric acid methyl ester (PC71BM) exhibited a PCE of 1.8%.

9185-106, Session 2

Extended and fused benzothiadiazole and benzotriazole units in semiconducting polymers for organic electronic applications *(Invited Paper)*

Miquel Planells, Iain McCulloch, Imperial College London (United Kingdom)

Semiconductor polymers applied to organic electronics field have attracted much attention from scientific community due to their potential low cost production, roll-to-roll solution process as well as their use in lightweight and flexible devices.[Chem. Rev. 2010, 110, 3] A well-known example is the semi-crystalline polymer poly-3-hexylthiophene (P3HT), which shows excellence performance both in solar cells and transistors due to the formation of right-sized crystalline and non-crystalline domains.

However, recently it has been shown that amorphous polymers can also show high mobilities by fusing aromatic rings together. In this case, superior backbone rigidity allows charges to be transported within the polymer chain and π-stacking (usually present in crystalline domains) is only occasionally required to relay the charge carriers. [Nature Commun. 2013, 4, 2238]

In this conference, we aim to present our current work on this topic. We will discuss the synthesis of a new class of polymers containing dithiophene-fused benzothiadiazole and benzotriazole electron-withdrawing units and co-polymerised with both indacenodithiophene (IDT) and cyclopentadithiophene (CDT) electron-rich moieties. The advantage of these polymers is that, despite being amorphous, hole and electron transport is similar and even more efficient than semi-crystalline polymers due to its rigid structure. We will then discuss their outstanding properties, characterized using a wide range of techniques, such as optical, electrochemical, thermal, crystallographic and computational methods. Finally, we will show the ambipolar performance of these polymers in field-effect transistors device.

9185-107, Session 2

Solution processable organic materials for flexible electronics *(Invited Paper)*

Rashmi Bhintade, Tomas G. Backlund, Stephen Bain, Aurelie Meneau, Piotr Wierzchowiec, Irina Afonina, Giles R. Lloyd, Mark James, Mark Verrall, Steven Tierney, David Sparrowe, Toby Cull, Merck Chemicals Ltd. (United Kingdom)

Formulation development suitable for OSC formulations suitable for high throughput large scale industrial printing techniques demonstrated. In conjunction with th semiconductor formulations, we have also developed compatible passive materials such as dielectrics, planarisation and passivation to enable an integrated stack. Passive materials incorporate properties desirable for integration, such as robust interlayer adhesion, patternability etc. Stable bias stress behaviour is demonstrated for integrated stacks of transistors with mobilities greater than amorphous silicon. Excellent uniformity is demonstrated over 2inch substrates - uniformity values with <10% spread in mobility obtained. Furthermore, we also show lifetime data of devices stored under ambient conditions.

9185-108, Session 2

Critical factors to achieve low voltage- and capacitance-based organic field-effect transistors

Hoichang Yang, Mi Jang, Inha Univ. (Korea, Republic of)

We reports that OFETs including low-Ci dielectrics can be operated at low voltages if highly conjugated organic semiconducting layers can b3e introduced to the hydroxyl-free dielectric surfaces. On grafted or cured polymer-assisted SiO2 dielectrics showing Ci = 10 - 11 nFcm-2, solution-processed triethylsiylethynyl anthradithiophene (TES-ADT) crystals were observed easily by the naked eye compared to micron-sized pentacene crystals. The resulting TES-ADT OFETs operated with a low voltage (|V| ≤ 5 V) showed high electrical performance (?FET, Vth, and SS values up to 1.3 cm2V-1s-1, approximately -0.5 V and ~ 0.2 Vdecade-1, respectively). In contrast, polycrystalline pentacene-based OFETs require much higher operating voltages (|V|>20 V). TES-ADT could be tuned intrisically with better pi-conjugated structures to transfer the charge-carriers, as determined by atomic force microscopy (AFM), X-ray diffraction, and in situ photo-excited charge-collection spectroscopy (PECCS).

9185-109, Session 3

New measurements of order and structure in semiconducting polymers *(Invited Paper)*

Dean M. DeLongchamp, Chad R. Snyder, Ryan C. Nieuwendaal, Brian A. Collins, National Institute of Standards and Technology (United States); Christine K. Luscombe, Prakash Sista, Shane D. Boyd, Univ. of Washington (United States)

In semiconducting polymers, the absolute extent of order and the nanoscale distribution of order are thought to be critical to charge transport properties. Although semiconducting polymers have been extremely well studied, there have been few attempts to quantify their absolute crystallinity. I will describe our efforts to quantify the enthalpy of fusion and melting temperature of high molar mass poly(3-hexylthiophene) (P3HT) fractions, such as those used in organic photovoltaic devices. Using a combination of differential scanning calorimetry (DSC) and 13C nuclear magnetic resonance spectroscopy (NMR), we studied P3HT with molar masses ranging from 3.6 kg/mol to 49 kg/mol. We extend this work to thin films, and include optical measurements of local order, and X-ray diffraction measurements of long-range order. An accurate heat of fusion model permits the measurement of absolute crystallinity by DSC. We will reduce this to practice using modern techniques that can to quantify endotherms for samples down to ≈0.2 mg, which is roughly the sample mass of a 2 cm ? 2 cm ? 100 nm film.

The distribution of ordered and disordered regions in thin polymer semiconductor films, especially at boundaries between domains, is perhaps even more impactful than their absolute crystallinity. The nanoscale distributions of polymer chain orientation and conformation, however, is typically unobservable even by the most powerful transmission electron microscopy techniques. I will describe our attempts to overcome this measurement gap using resonant soft X-ray scattering (RSoXS). By practicing RSoXS on well-understood model materials such as poly[2,5-bis(3-tetradecylthiophen-2-yl)thieno[3,2-b]thiophene] (pBTTT), we can discern details of the order and orientation within interdomain regions that may relate directly to charge transport.

9185-110, Session 3

Semiconducting:insulating polymer blends: processing, structure and opportunities for the OFET field *(Invited Paper)*

Natalie Stingelin, Imperial College London (United Kingdom)

Blends and other multicomponent systems are used in various polymer applications to meet multiple requirements that cannot be fulfilled by a single material. In polymer optoelectronic devices it is often desirable to combine the semiconducting properties of the conjugated species with the properties of certain commodity polymers, such as mechanical robustness, pronounce hydrophobicity and low gas diffusion. Here we investigate bicomponent blends comprising high-mobility, polymeric semiconductors, such as diketopyrrolopyrrol derivatives (DPP-T-TT) and selected semicrystalline commodity polymers, and show that, owing to a highly favourable, crystallization-induced phase segregation of the two components, we can reach low-percolating network systems similar to poly(3-hexylthiophene):high-density polyethylene (HDPE) blends.1,2 Focus of the presentation will be on the effect of the insulator on the sub-threshold voltage, bias stress and On-Off ratio as well as long-term environmental device stability of such DPP-T-TT devices.

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9185-111, Session 3

Mechanically induced heterogeneous nucleation for patterned organic semiconducting thin films

Liyang Yu, Muhammad R. Niazi, Aram Amassian, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Recent reports for organic semiconducting devices such as field-effect transistors (FETs) indicate encouragingly superior electronic performance over their amorphous silicon based counterparts. [1] However, obtaining a high performance patterned active structure with a high throughput roll-to-roll compatible method remains to be fully developed. For low cost circuits this issue can be critical and may sacrifice the high electronic performance.

Here we introduce a straightforward mechanical method to provide nucleation sites, and thereby control the macroscopic crystal morphology of a high performance organic small molecule semiconductor – 5,11-Bis(triethylsilylethynyl)anthradithiophene (TES ADT).[2] This method takes advantage of the various solid state phases of TES-ADT.[3] Starting with its amorphous as-cast structure with high speed blade coating following by a series of thermal and solvent-vapor annealing and stamping steps, we produced a patterned structure with isolated high performance areas with identical morphology on the FET channels. Hence, the spread of device performance was reduced to a more narrow range. Interestingly, this patterned structure also slightly improved the electronic performances of the FET devices, though the origin of this improvement is yet to be explored. A small anisotropy was found in two perpendicular directions of charge transport which agreed with literature.[4]

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9185-112, Session 3

Nanoaggregates of poly(3-hexylthiophene): morphology-electrical properties relation

Urszula Bielecka, Krzysztof Janus, Marcin Sojka, Juliusz Sworakowski, Wojciech Bartkowiak, Wroclaw Univ. of Technology (Poland)

Electrical properties of poly(3-hexylthiophene) (p3ht) may be controlled by changing morphology and molecular organization of polymer chains in solution (e.g. via aggregation) and/or in thin films. Recent studies demonstrate that physicochemical properties of solvent together with sample history (solution preparation, storage conditions) affect the aggregation processes and, consequently, electrical properties of deposited samples.

In this work, we analyze formation kinetics of p3ht nanofibers in chloroform solutions, in function of nominal p3ht concentration, by following the temporal evolution of red-shifted satellites of the main peak in the UV-Vis spectra.

The solutions, differing in the nominal concentrations of p3ht and in the storage time, have been used to fabricate organic field effect transistors (oFETs). The charge carrier mobilities (?FET) were determined from the transfer characteristics. In samples fabricated using freshly made solutions, ?FET was of the order of 10-5-10-4 cm2/Vs, whereas use of aged solutions resulted in a substantial increase of ?FET, depending on the nominal p3ht concentration. The mobilities in samples obtained using the aged 10 mg/ml solution amounted to ca. 0.04 cm2/Vs, whereas in samples deposited from the aged solution of the lowest concentration (1 mg/ml) the mobility was lower by ca. two orders of magnitude.

The results obtained on samples fabricated using the "conventional" spin-coating were compared with those obtaining with other frequently employed techniques (spray casting, off-center spin coating and painting).

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9185-113, Session 4

Microstructure and doping of organic semiconductors *(Invited Paper)*

Michael L. Chabinyc, Univ. of California, Santa Barbara (United States)

Significant progress has also been made to understand their ultimate limits of carrier mobility in organic thin film transistors. We have studied electrical doping of both p- and n-type semiconducting polymers using molecular compounds and find evidence that they are limited by morphological factors rather than the efficiency of charge generation of the dopant. Grazing incidence wide angle scattering and electron microscopy reveal phase separation or molecular intercalation depending on the molecular structure of the dopant. Measurements of the thermopower reveal important details about transport mechanisms that are difficult to discern from electrical conductivity alone. Recent work on microstructural changes in high performance semiconducting polymers during doping and the impact on transport mechanisms will be presented.

9185-114, Session 4

Observation of a distinct surface molecular orientation in films of a high mobility conjugated polymer

Christopher R. McNeill, Monash Univ. (Australia); Torben

Schuettfort, Univ. of Cambridge (United Kingdom); Lars Thomsen, Australian Synchrotron (Australia)

The molecular orientation and microstructure of films of the high-mobility semiconducting polymer poly(N,N-bis 2-octyldodecylnaphthalene-1,4,5,8-bis dicarboximide-2,6-diyl-alt-5,5-2,2-bithiophene) (P(NDI2OD-T2)) are probed using a combination of grazing-incidence wide-angle x-ray scattering (GIWAXS) and near-edge x-ray absorption fine-structure (NEXAFS) spectroscopy. In particular a novel approach is used whereby the bulk molecular orientation and surface molecular orientation are simultaneously measured on the same sample using NEXAFS spectroscopy in an angle-resolved transmission experiment. Furthermore, the acquisition of bulk-sensitive NEXAFS data enables a direct comparison of the information provided by GIWAXS and NEXAFS. By comparing the bulk-sensitive and surface-sensitive NEXAFS data a distinctly different molecular orientation is observed at the surface of the film compared to the bulk. While a more 'face-on' orientation of the conjugated backbone is observed in the bulk of the film, consistent with the lamella orientation observed by GIWAXS, a more 'edge-on' orientation is observed at the surface of the film with surface-sensitive NEXAFS spectroscopy. This distinct edge-on surface orientation explains the high in-plane mobility that is achieved in top-gate P(NDI2OD-T2) field-effect transistors (FETs), while the bulk face-on texture explains the high out-of-plane mobilities that are observed in time-of-flight and diode measurements. These results also stress that GIWAXS lacks the surface sensitivity required to probe the microstructure of the accumulation layer that supports charge transport in organic FETs and hence may not be appropriate for correlating film microstructure and FET charge transport.

9185-115, Session 4

Beyond conventional organic transistors: novel approaches with improved performance and stability *(Invited Paper)*

Bjorn Lüssem, Kent State Univ. (United States); Max L. Tietze, Technische Univ. Dresden (Germany); Axel Fischer, Institut fuer Angewandte Photophysik, TU Dresden (Germany); Paul Pahner, Technische Univ. Dresden (Germany); Hans Kleemann, Technische Univ. Dresden (Germany) and Novaled GmbH (Germany); Alrun Günther, Daniel Kasemann, Karl Leo, Technische Univ. Dresden (Germany)

Organic electronics hold the promise of enabling the field of flexible electronics. Unfortunately its key element, the organic field effect transistor (OFET), is still lacking in performance and stability. In this presentation, we will introduce novel organic transistor concepts that open new directions to improve the performance of OFETs.

The transistors are based on the technology of molecular doping (Walzer et al. Chem.Rev. 107, 1233 (2007)). Using an improved co-evaporation technique, we reach extremely low molar doping ratios of almost 10-5. At these low concentrations, doping in pentacene behaves similarly to doping in inorganic semiconductors, and we can identify the impurity saturation and impurity reserve regimes (Tietze et al.; in preparation). Besides, filling of existing trap distributions is observed (Pahner et al., Phys.Rev. B. 88 (2013)).

Several novel organic transistor concepts based on doping will be presented. The realization of organic inversion transistors (Lussem et al.; Nature Communications 2, 2775 (2013)) as well as organic junction field effect transistors (Lussem et al.; AFM, DOI: 10.1002/adfm.201301417 (2014)) is demonstrated. The operation and potential of these transistors is discussed and benchmarked to conventional OFETs.

However, it is challenging to aggressively scale the channel of these transistors, since they are processed with the transistor channel in-plane. It will be shown that organic transistors can alternatively be processed vertically (Kleemann et al.; Small 9, 3670 (2013)), which allows for reducing the channel length to the sub-?m regime. Performance, design rules and prospects of this novel design concept are discussed.

9185-116, Session 4

High-performance organic transistors for printed circuits *(Invited Paper)*

Jun Takeya, Osaka Univ. (Japan)

The idea of printing CMOS integrated circuits, which has been discussed for decades as a wish for the future, may be just around the corner for realistic applications such as RFID tags. With the advanced technologies of solution-processed organic semiconductor circuits, operation at more than 20 MHz for each gate in circuits is now realistic using printable semiconductors with the mobility higher than 10 cm2/Vs on plastic substrates. Therefore, fundamental techniques for low-price moderately integrated circuits like memory-accessing logics in RFID tags are already available with the "printed LSIs" (pLSIs).

This progress was actually driven by recent development of high mobility and chemically stable new compounds and by proper understanding of charge carrier transport in such organic semiconductors. Notably, the breakthrough in chemistry was in parallel with the paradigm shift in understanding physics that realization of band transport is evidenced with the development of field-effect transistors of organic semiconductor single crystals. The organic single-crystal transistors have first contributed to exhibit the intrinsic carrier mobility for each material, excluding extrinsic effects of grain boundaries in polycrystalline organic semiconductor films, which were much more commonly studied. More recently, technology of growing crystalline films from solution of organic molecules, the single-crystalline organic semiconductor films, or organic crystal "wafers", becomes the reliable and high-performance source for the printed LSIs. Using finely patterned semiconductor channels fabricated on the continuous crystal films, successful rectification and identification are demonstrated at 13.56 MHz with printed organic CMOS circuits for the first time.

9185-118, Session 4

Solution-processing of organic semiconductor thin films with controlled polymorphism *(Invited Paper)*

Aram Amassian, King Abdullah Univ. of Science and Technology (Saudi Arabia)

Recent progress in the design of organic semiconductors (OSC) has made it easy to routinely fabricate organic thin film transistors (OTFTs) with carrier mobility in the 1-10 cm2/Vs range. Further developments in the solution-based fabrication methods of OSC thin films, such as by solution-shearing, have also been credited with important improvements in the carrier mobility of small-molecule OSCs. Structural investigations of thin films fabricated by solution shearing credit the formation of different polymorphs of the OSC thin film by the solution-shearing method for resulting in the measured performance improvements. In situ investigations of the crystallization process performed by microbeam grazing incidence wide angle x-ray scattering suggest that physical confinement of the solution during crystallization is responsible for altering and selecting the polymorph of the polycrystalline OSC thin film. We show experimental and computational evidence suggesting the thermodynamic landscape during crystallization may be modified by the choice of the solvent, thus favoring formation of different polymorphs. We further demonstrate that careful selection of solvent and blending with insulating polymers can induce polymorphism, leading to high performance OTFT devices.

9185-119, Session 5

Ultraflexible organic thin-film transistors on 1-micron thick plastic substrates *(Invited Paper)*

Tsuyoshi Sekitani, The Univ. of Tokyo (Japan)

This talk will provide the fabrication and electrical, mechanical characteristics of 1-mm-thick ultraflexible organic transistor and demonstrated the imperceptible organic electronic systems for biomedical sensors [1-3].

High-performance organic thin-film transistors (TFT) directly onto 1.2 μm thick polymer substrates exhibit excellent carrier mobilities of 3 cm2/Vs and are operated within 3V. A hybrid oxide gate dielectric enables extreme mechanical resilience that allows our electronic foils to be bent into radii of 5 μm and less and form an intimate contact with arbitrary shapes including human skin. In bio-medical applications, including in-vivo sensing of bio-signals, ultrathin electronic foils must operate at elevated temperatures and in aqueous environments. At just 2 μm thickness our devices exhibit remarkable environmental stability, withstanding thermal annealing up to 170 °C and remain fully functional when completely immersed into salt water and continuously operated for more than two weeks.

For the demonstration, we report 1.2-μm-thick large-area active matrix amplifier, which can be crumpled like paper and operated at elevated temperatures and in aqueous environments. By taking advantage of an ultraflexible and compliant amplifier that can amplify biological signals by 500, we developed 64-channel active matrix electrocardiogram and electromyogram monitoring systems. Ultrathin electronics with a total thickness of approximately 1–2 μm allow bending to a radius of 10 μm.

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9185-120, Session 5

Towards low-voltage organic field-effect transistors (OFETs) with solution-processed high-k dielectric and interface engineering *(Invited Paper)*

Jianbin Xu, Yaorong Su, The Chinese Univ. of Hong Kong (Hong Kong, China); Weiguang Xie, Jinan Univ. (China)

Although tremendous progress has been made in improving the performance of organic field-effect transistors (OFETs), the high operation voltage resulting from the low gate areal capacitance of SiO2 remains a severe limitation that hinders OTFTs' development in practical applications. In this regard, developing new materials with high-k characteristics at low cost is of scientific and technological importance in the area of both academia and industry. Here, we introduce a simple solution-based technique to fabricate high-k metal oxide dielectric system (ATO) at low-temperature, which is applicable to realizing low-voltage operation of OTFTs. Meanwhile, it is well known that the properties of the dielectric/semiconductor and electrode/semiconductor interfaces are crucial in controlling the electrical properties of OTFTs. By optimizing the above two interfaces with octadecylphosphonic acid (ODPA) self-assembled monolayer (SAM) and in-situ modified Cu with low-cost, markedly improved device electrical performance is attained in our low-voltage OFETs. Organic electronic devices on flexible substrates have attracted much attention due to their low-cost, rollability, large-area processability, and so on. One of the most critical issues in realization flexible OTFTs is the integration of gate dielectrics with flexible substrates. We have successfully incorporated the high-k dielectric with Au coated flexible polyimide (PI) substrate. By utilizing the interface engineering, outstanding electrical performance is achieved in flexible devices. In addition, the mechanical flexibility and reliability of the devices are studied in detail. Our studies demonstrate an effective way to realize low-voltage, high-performance OFETs at low-cost.

9185-121, Session 5

Study of the improvements in the electrical performance of solution-processed metal oxide thin-film transistors using self-assembled monolayers

Jin-Woo Park, Hyeong-Jung Kim, Dae-Hwan Kim, Mi-Jung Lee, Kookmin Univ. (Korea, Republic of)

A thin film transistor (TFTs) with metal oxide semiconductor has transparency and high mobility to be used in display devices as back-plane these days. One of the fabrication methods of metal oxide semiconductor being most actively studied is solution process (sol-gel method) due to advantages of low-cost, fast and easy steps with good uniformity to apply to a roll-to-roll process. , Although solution process requires high thermal energy to form an M-O bond various methods for low-temperature annealing process suggested recently enhance the possibility of industrial applications.

This report is focused on the optical investigation of charge traps in solution processed metal oxide TFT with probing electronic properties. We can find out density of state (DOS) with monochromatic photonic capacitance-voltage (MPCV) measurement which is simple and powerful method for figuring charge trapping state. And for the comparative study with enhanced TFT device, self-assembled-monolayers (SAMs) are employed on insulator layer by simple dipping process to change interface property. So, improvement of device with such effective method can be proved by electronic and photo–electronic method for electronic property as well as stability

9185-122, Session 5

Nonvolatile organic transistor memory devices based on nanostructured polymeric materials *(Invited Paper)*

Wen-Chang Chen, Mau-Shen Lu, Chien Lu, Meng-Hsien Li, National Taiwan Univ. (Taiwan); Cheng-Liang Liu, National Central University (Taiwan)

Organic memory devices have attracted significant scientific interest due to their advantages of the structural flexibility, processability, light weight, and three-dimensional stacking capability. The configuration of organic field effect transistor (OFET) memory devices is the conventional transistors with an additional charge storage layer between a semiconductor layer and a gate dielectric layer. We have explored the nonvolatile OFET memory devices through the nanostructured organic semiconductors, donor-acceptor polymer electrets, and star-shape polymer electrets. Here, electrospun semiconducting nanofibers of poly(9,9-dioctyl-fluorene-co-bithiophene) or poly(3-hexylthiophene):gold nanoparticles (Au NPs) hybrids and nanowires of N,N'-bis(2-phenylethyl)-perylene-3,4:9,10-tetracarboxylic diimide are presented. Compared to spin-coated thin films, both ES nanofibers and nanowires could have a higher electrical field to facilitate the formation of dipole moment at the interface, leading to an enhanced memory windows. The Au NPs were employed as localized charge traps across the different channel and program/erase the device towards low conductance (OFF)/ high conductance (ON) states under the applied electrical field. The dipole on the self-assembled monolayer on Au NPs modify the work function and manifest the degree of negative threshold voltage shifting. The morphology of nanofibers/nanowires also affected the memory characteristics significantly, including diameter, orientation, and order/ disorder domain. The hybrid nanofiber transistor memories on the PEN polymer substrates operating at a low operation voltage of ±5 V exhibited a 3.5~10.6 V threshold voltage shifting, more than 104 s data retention, even under the bending conditions (radius: 5~30 mm) or 1000 repetitive bending cycles.

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9185-123, Session 5

Circularly-polarized light detecting phototransistors based on a helically-shaped chiral organic semiconductor

Alasdair J. Campbell, Ying Yang, Rosenildo Correa da Costa, Matthew J. Fuchter, Imperial College London (United Kingdom)

Organic field-effect transistors (OFETs), in which the active semiconducting layer is an organic material, allow the simple fabrication of ultra-thin, compact devices. Planar aromatic molecules, such as pentacene and the other acenes, have been widely used in transistors. Here we report, for the first time, an OFET based on an asymmetrically-pure helically-shaped chiral aromatic molecule known as a helicene. OFETs with a helicene semiconductor layer are solution-processible and have well-behaved device characteristics. Importantly, we find a highly specific photo-response to circularly polarised (CP) light, which is directly related to the handedness of the helicene molecule (Nature Photonics vol. 7, p. 634 (2013)). Chiral, circularly polarized (CP) light is central to many photonic technologies, including CP-ellipsometry based tomography, optical communication of spin information, and quantum-based optical computing and information processing. To develop these technologies to their full potential would require the miniaturization and integration of suitable chiral photo-detecting devices. We believe the helicene OFETs open up a unique possibility for CP detection in highly integrated photonic technologies.

9185-124, Session 6

Solution-grown organic single-crystalline p-n junctions *(Invited Paper)*

Hanying Li, Congcheng Fan, Zhejiang Univ. (China)

Single-crystalline p-n junctions with contacting two single-crystals of organic semiconductors are expected to show superior charge transport property as well as exciton generation/dissociation ability. Thus, these p-n junctions are promising high-performance materials for opto-electronic applications such as solar cells. However, the single-crystalline p-n junctions are difficult to prepare. Intuitively, crystallization generally requires relatively clean environments and crystallization of “p” and “n” two components together tends to interrupt each other. Here, we describe how to grow, from solutions, organic single-crystalline p-n junctions in a single step from a mixed solution of p-type and n-type molecules. Basically, one crystal (e.g., n-type crystal) grows first and the other (e.g., p-type crystal) with slower growth rate nucleates on the former. Subsequently, both crystals grow simultaneously into single-crystalline p-n junctions. We have prepared single-crystalline p-n junctions based on 2,7-dioctyl[1]benzothieno[3,2-b][1]benzothiophene (C8-BTBT), C60 (n-type) and several other organic molecules. These junctions exhibited ambipolar charge transport characteristics in field-effect transistors (FETs). This work provides a platform to deepen the fundamental knowledge and to fabricate high-performance electronic devices of organic semiconductors.

9185-125, Session 6

Exciton fission, fusion and long-range triplet exciton diffusion in molecular crystals: impact on photoconductivity and photoluminescence of organic semiconductors *(Invited Paper)*

Vitaly Podzorov, Rutgers, The State Univ. of New Jersey (United States)

In this talk, I will discuss some important aspects of photo-physics of organic semiconductors, including exciton fission, fusion and the recently observed long-range triplet exciton diffusion in highly ordered organic crystals. In particular, it has been observed that diffusion of triplet excitons can occur over the distances of several micrometers, excitons dissociate at crystal surfaces and thus generate surface photocurrent, without generating photocurrent in the bulk [1]. In addition, more recently we have observed a clear evidence of interaction of diffusing triplets with defects (exciton harvesting by defects) [2,3], with each other (triplet-triplet annihilation) and with mobile charge carriers (exciton-charge recombination) [4] in photoluminescence and photoconductivity measurements. In combination with time-resolved measurements, these observations strongly suggest that long-lived triplet excitons are indeed generated in certain molecular crystals via singlet fission, and the diffusion and interaction of these triplets with themselves and other species are the fundamental processes governing the photophysics of highly-ordered organic semiconductors.

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9185-126, Session 6

Patterning of high-quality polycrystalline rubrene based on electron-irradiated polystyrene and its applications for organic thin-film transistors

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We have developed an unprecedented method for patterning of polycrystalline rubrene thin-film by electron irradiation and post-annealing crystallization process. For these purpose we adopted cross-linkable polymer, polystyrene as a buffer layer on a SiO? dielectric and selectively electron-irradiated it with a mask. As a result, polystyrene only at irradiated area was cross-linked and polystyrene patterns with different thermal stability were fabricated without developing process.

After thermal evaporation of rubrene on pre-patterned polystyrene layer in high vacuum, amorphous rubrene thin-film was placed continuously on patterned polystyrene layer. By successive abrupt-heating of rubrene on pre-patterned polystyrene layer at the orthorhombic crystallization temperature of rubrene, only rubrene molecules on irradiated area were crystallized as an orthorhombic phase with grain sizes of several hundreds of micrometer. Oppositely, rubrene molecules on non-irradiated area were crystallized as a non-platy triclinic or amorphous phase because most of heat is consumed to the chain movement of non-cross-linked polystyrene and the rubrene molecules were not thermal-crystallized enough.

With these selectively grown rubrene thin-films of different phases of crystallization, the patterned rubrene thin-film transistors were fabricated. Because of their hugely different charge transporting properties as each crystal phase, the conducting channels were formed at orthorhombic phase rubrene which is crystallized on selectively electron-irradiated polystyrene pattern. The patterned polycrystalline rubrene thin-film transistor showed a field-effect mobility of 2.5 cm?/Vs with on/off ratio higher than 10?. Our noble patterning approach can be utilized at various organic materials and nano-patterning of semiconductor with using direct electron beam writing is also expected.

9185-127, Session 6

Terahertz study of hole transport in pentacene thin films

Roland Kersting, Stefan G. Engelbrecht, Markus Prinz, Thomas R. Arend, Ludwig-Maximilians-Univ. München (Germany)

Thin films of organic semiconductors are usually polycrystalline on sub-micrometer scale. The high density of grain boundaries as well as deep traps efficiently hinder charge transport on macroscopic scales and lead to low mobilities in electronic characterization. Terahertz spectroscopy is an alternative tool for characterizing semiconductor thin films. It provides the intrinsic transport properties of the material, since bound charges as well as transport across grain boundaries do not contribute to the high-frequency response of charge carriers.

Hole transport in pentacene is studied on varactor structures that allow for the injection of holes. The pentacene films have a thickness of about 50 nm and show sub-micrometer crystallites. Electronic characterization provides hole mobilities of about 0.01 cm2/Vs, which indicates efficient scattering at grain boundaries. For measuring the intrinsic transport properties, the differential transmission of THz pulses is recorded when switching the carrier density injected into the pentacene. Both, real and imaginary conductivities are deduced from the differential signals.

Terahertz data recorded on pentacene reveal hole mobilities of about 5 cm2/Vs, which exceed the results of the electronic characterization by about three orders of magnitude. We attribute this difference to the fact that THz spectroscopy maps the intrinsic transport properties of pentacene. Additionally, we observe that the imaginary conductivity is negative, which is incompatible with the model of Drude transport. Calculations based on effective medium theory suggest a percolated transport within the accumulation layer of pentacene thin films.

9185-128, Session 6

Tuning of energetic barrier at semiconductor/dielectric interface to enhance gate-bias stress stability of organic field-effect transistors

Jiye Kim, Pohang Univ. of Science and Technology (Korea, Republic of); Se Hyun Kim, Youngnam Univ. (Korea, Republic of); Chan Eon Park, Pohang Univ. of Science and Technology (Korea, Republic of)

We report that the correlation between dielectric surface and the operational reliability of organic field-effect tranistors (OFETs). The bias stress stabilities of the OFETs with methoxy-, methyl-, and fluoro-functional styrene treated dielectric surface are investigatied. To investigate of charge transfer from semiconductor into dielectric layer under sustain bias stress, we performed ultraviolet photoelectron spectroscopy (UPS). An intresting results shows that the higher variation of highest occupied molecular orbitals (HOMO) between pentacene semiconductor and fluoro-functional styrene dielectric lead to highly stable OFETs. The bias stability and variation follows the order; fluoro-> methyl- > methoxyl-functional styrene. As a result, we suggest the energetic barriers which highly related with the variation for carrier transfer to dielectric layer. The energetic barriers are only influenced by variation of HOMO. Because applying low bias voltage can not provide sufficient energy for crossing the energetic barrier, all device shows highly bias stress stable behaviors. As sustained bias voltage is increased, the device exhibits lower stability according to variation magnitude of HOMO between pentacene and polymer dielectrics.

9185-129, Session 7

Toward intrinsically stretchable organic semiconductors: mechanical properties of high-performance conjugated polymers *(Invited Paper)*

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The fragility of many modern organic semiconductors might limit their applicability in applications demanding mechanical compliance. For example, many pure polymers, polymer-fullerene blends, and the transparent conductor indium tin oxide all fracture at tensile strains of two percent or less on compliant substrates. The design of organic semiconductors that can be deformed significantly would facilitate roll-to-roll production, mechanical robustness for potable applications, conformal bonding to curved surfaces other than cylinders (i.e., for implantable biomedical devices), and would enable large-scale solar farms based on ultra thin organic modules that can survive forces of the outdoor environment. This paper describes our efforts to understand and control the structural parameters that influence the mechanical properties of modern conjugated polymers. Our conclusions include the effect of the side chain in determining the elasticity, ductility, and adhesion of polymers and their blends with fullerenes, and how this effect can be predicted by theory. Ultra-compliant materials are used for the first time in solar cell that can be stretched and conformed to hemispherical surfaces without damage. We also describe the synthesis of all-conjugated block copolymers whose goal is to maximize both electronic properties and mechanical compliance. A new polymerization based on cross-coupling of conjugated "macromonomers" could enable block-copolymer-like materials from step-growth polymerizations. Mechanical and photovoltaic properties of these segmented copolymers are also reported. Our results should inform the engineering of new semiconducting polymers for flexible and stretchable applications.

9185-130, Session 7

Electrically engineered polymer-carbon hybrid heterojunction for high-performance printed transistors *(Invited Paper)*

Do Hwan Kim, Soongsil Univ. (Korea, Republic of); Gyu Won Kang, Department of Organic Materials and Fiber Engineering, Soongsil University (Korea, Republic of); Hyeon-Jin Shin, Materials and Devices Laboratory, Samsung Electronics (Korea, Republic of); Woo-Jae Kim, Department of Chemical and Environmental Engineering, Gachon University (Korea, Republic of)

Molecularly hybridized materials composed of polymer semiconductors (PSCs) and single-walled carbon nanotubes (SWNTs) may provide a new platform to exploit an advantageous combination of semiconductors, which yields electrical properties that are not available in a single component system. In this talk, we demonstrate high-performance ink-jet printed hybrid transistors with an electrically engineered heterostructure by using specially designed PSCs and semiconducting SWNTs (sc-SWNTs) whose system achieved a high mobility of 0.23 cm2V-1s-1, no Von shift, a low off-current, and good bias-stability. We also revealed that binding energy between PSCs and sc-SWNT was strongly affected by side-chain length of PSCs, leading to the formation of homogeneous nanohybrid film. Eventually, understanding of electrostatic interactions in the heterostructure and experimental results suggest criteria for the design of nanohybrid heterostructures.

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Planning, Korea. The authors acknowledge Prof. Kilwon Cho and Dr. Hyo Sug Lee for collaboration on the analysis of x-ray diffraction and material simulation, respectively.

9185-131, Session 7

Highly stretchable polymer transistors consisting entirely of stretchable device components *(Invited Paper)*

Unyong Jeong, Yonsei Univ. (Korea, Republic of)

This presentation deals with the fabrication of an array of highly stretchable polymer transistors made entirely of stretchable components. The transistors were constructed of stretchable Au nanosheet electrodes, polyelectrolyte gel for the gate dielectric, metal nanowires for the circuit, and nanofibril-based stretchable channel materials. This talk will present the issues of the components regarding with the stretchability and mechanical performance. The combination of those stretchable components provided a high hole mobility (?=18 cm2/Vs) even at 70% strain and showed excellent electrical stability over 1,500 stretching cycles.

9185-132, Session 8

Comparison of conductor and dielectric inks in printed organic complementary transistors *(Invited Paper)*

Tse Nga Ng, Ping Mei, Palo Alto Research Center, Inc. (United States); Gregory L Whiting, Palo Alto Research Center (United States); David E. Schwartz, Palo Alto Research Center, Inc. (United States); Biby Abraham, Yiliang Wu, Xerox Research Center Canada (Canada); Janos Veres, Palo Alto Research Center, Inc. (United States)

Digital, additive printing of soluble materials allows rapid fabrication of organic transistors. With the recent improvements in printed devices, it is now possible to build independent sensor systems out of printed devices. There are new challenges with integrating multiple devices into systems, because the system designs should take into account the characteristics of printed transistors, such as device variations and stability. Here we took a systematic approach to model printed organic devices, and from the modeling and simulations we have designed and fabricated prototypes of temperature sensors tags based on printed organic complementary transistors. In this presentation I will discuss the design rules we learned in the course of developing this sensor platform.

In addition to the need for design rules, there is a strong demand to lower circuit operational voltage and reduce power requirements. This presentation will describe our approach to print low-voltage electronic devices using high-k PVDF terpolymer dielectric with k up to 30. This approach enables the circuits to operate at below 5V, eliminates the gate leakage issues with thin dielectrics, and improves yield compared to the typical inkjet-printed circuits.

9185-133, Session 8

Tuning molecular orientation and crystal structure via post-deposition processing to optimize charge transport in thin-film transistors *(Invited Paper)*

Anna M. Hiszpanski, Princeton Univ. (United States); Arthur R. Woll, Cornell Univ. (United States); Nan Yao, Yueh-Lin Loo, Princeton Univ. (United States)

Though both the molecular orientation and crystal structure of organic semiconductors are known to impact charge transport in thin-film devices, controllably accessing different polymorphs and varying the out-of-plane molecular orientation remain challenging, requiring careful selection of film deposition conditions, film thickness, and substrate chemistry. Without necessitating any specification of these parameters, we can access three polymorphs of contorted hexabenzocoronene, HBC, in thin films and independently vary the distributions of out-of-plane molecular orientation. Starting with a thermally-evaporated, amorphous HBC film, thermal annealing induces HBC to crystallize with the known P21/c crystal structure, which we refer to as polymorph I. THF-vapor annealing instead induces the film to adopt polymorph II, a previously unobserved crystal structure. By subjecting the films to additional rounds of solvent-vapor and thermal annealing, respectively, we can transform polymorph I to polymorph II, and polymorph II to polymorph II'. Though the crystal structure is tuned through sequential rounds of post-deposition processing, the out-of-plane molecular orientation is primarily determined by the first processing step. Thus, by applying different sequences of thermal and solvent-vapor annealing, we can access films having different polymorphs but the same molecular orientation, and also films having the same polymorph but different molecular orientations, allowing us to decouple the relative contributions of each. In the case of HBC, polymorphism and molecular orientation are equally important; with the optimal polymorph and molecular orientation each improving the field-effect mobility of thin-film transistors by an order of magnitude.

9185-134, Session 8

High performance transparent organic thin film transistors grow by a novel off-centre spin-coating method

Jinsong Huang, Yongbo Yuan, Univ. of Nebraska-Lincoln (United States); Gaurav Giri, Alexander L. Ayzner, Arjan P. Zoombelt, Stanford Univ. (United States); Stefan C. B. Mannsfeld, SLAC National Accelerator Lab. (United States); Jihua Chen, Oak Ridge National Lab. (United States); Dennis Nordlund, Michael F. Toney, SLAC National Accelerator Lab. (United States); Zhenan Bao, Stanford Univ. (United States)

The carrier mobility is sensitively influenced by the crystallinity and the molecular arrangement in a crystal lattice. Here we report the formation of a highly aligned, metastable crystal packing structure (likely a polymorph) of C8-BTBT by a simple off-centre spin-coating (OCSC) method from a blended solution of C8-BTBT and polystyrene (PS). In the OCSC process, the substrate is placed away from the center of the spin-coater. The centrifugal force is almost unidirectional over the whole substrate. This method produced highly aligned meta-stable C8-BTBT crystals, as confirmed by polarized optical absorption spectra, grazing incidence X-ray diffraction and Near-edge X-ray Absorption Fine-Structure Spectroscopy. An ultra-high maximum hole mobility of 43 cm^2/Vs and an average hole mobility of 25 cm^2/Vs were obtained. These meta-stable C8-BTBT films were observed to maintain its structural integrity up to 80 ?, and the subsequent fabricated devices were stable under both DC and AC bias at room temperature. We found the hole mobility of C8-BTBT has a strong dependence on the film thickness. The high mobility OCSC C8-BTBT films (10~18 nm) were considerably thinner than what previously studied. Our study indicate that the obtained very high hole mobility in C8-BTBT:PS blend films mainly results from the highly aligned crystalline grains with a slightly reduced in-plane intermolecular spacing. The obtained mobility also clearly benefited from PS blending via the formation of vertical phase separation, as confirmed by the cross-sectional TEM and SEM images, where the PS segregated to the dielectric/semiconductor interface may have helped to reduce interfacial traps.

9185-135, Session 8

Printed organic field effect transistors with patterned polyethylenimine layers

Amir Dindar, Georgia Institute of Technology (United States); Mathieu Fenoll, Solvay S.A. (Belgium); Canek Fuentes-Hernandez, Talha M. Khan, Anthony J. Giordano, Junxiang Zhang, Seth R. Marder, Bernard Kippelen, Georgia Institute of Technology (United States)

High performance, air-stable n- and p-channel organic-field effect transistors (OFETs) need to be realized by scalable printing techniques to fulfill their commercial potential. High performance n-channel OFETs are most challenging because n-channel organic materials and low work function (WF) metals, required to minimize contact resistance, are commonly very sensitive to air. Recently we reported that air stable low WF electrodes can be achieved by coating high WF conductive materials with amine-containing non-conjugated polymers, such as ethoxylated polyethylenimine (PEIE). When applied to n-channel OFETs, unpatterned ultrathin PEIE films by spin-coating yielded drastic reductions of the threshold voltage (VTH) compared to OFETs with uncoated source and drain (S/D) electrodes, but thicker PEIE films lead to a drastic increase of the off-current.

Here, we report on the performance of inkjet printed top-gate OFETs wherein PEIE is selectively printed on the S/D or inside the channel. Reduced VTH and increased mobility values are observed when PEIE is applied to the S/D, while the off-current increases when applied solely to the channel; suggesting the possibility of n-doping. A shift in the photoemission cut-off on ultraviolet photoemission spectroscopic studies confirms the strong interaction between the organic semiconductor and PEIE. These results indicate that PEIE improves OFET performance not only as a result of a WF reduction but potentially by contact doping when patterned onto the S/D. Similar results will be reported on a variety of organic semiconductors and the implication of the use of amine-containing non-conjugated polymers in printed electronic devices will be discussed.

9185-136, Session 8

Organic Field-Effect Transistor Circuits with Electrode Interconnections using Reverse Stamping

Sangmoo Choi, Canek Fuentes-Hernandez, Minseong Yun, Amir Dindar, Talha M. Khan, Cheng-Yin Wang, Bernard Kippelen, Georgia Institute of Technology (United States)

Organic field-effect transistors (OFETs) are paving the way towards the commercial production of circuits and systems for flexible electronics. Improvements in OFET performance are now being followed by improvements in device stability and the development of low-cost scalable fabrication methods. Recently, we showed that top-gate OFETs with a CYTOP/Al_2O_3 (by atomic layer deposition, ALD) bi-layer gate dielectric exhibit improved environmental and operational stability in air and in water; enabling their use in reusable chemical and biological sensors in aqueous solutions. The use of ALD processed layers introduces challenges for patterning of devices required to produce functional circuits and systems. Current patterning methods for ALD layers require harsh and expensive methods incompatible with OFET fabrication.

Here, we introduce a non-vacuum low-cost reverse stamping method which allows patterning of high-k inorganic dielectric films produced by ALD and of bi-layer gate dielectric layers used in highly stable top-gate OFETs. Unlike the conventional stamping methods used in soft lithography, wherein films are transferred by a stamp, the proposed method uses a stamp to selectively remove parts of the insulating film. To show the potential of this method we fabricated circuits based on top-gate OFETs with a bi-layer gate dielectric. We demonstrate the fabrication and operation of logic inverters, NOR2 gates, ring oscillators, and 2-to-4 decoder circuits following this approach. The proposed reverse stamping method is a step forward towards the realization of OFET circuits with the environmental and operational stability needed for practical commercial applications.

9185-117, Session PWed

Investigation of charge injection characteristics in diketopyrrolopyrrole ambipolar semiconducting polymers

Seonjeng Lee, Mijung Lee, Kookmin Univ. (Korea, Republic of); Sukhyun Jung, Jin-Kyun Lee, Inha Univ. (Korea, Republic of); Cheawon Kim, Kookmin Univ. (Korea, Republic of)

Recently, organic semiconductors have attracted much attention due to their future electronic application. There have been a lot of studies on organic field effect transistor (OFET) fabricated with printable and solution processed polymer thin films. OFETs have generally been used as unipolar devices. Previsouly, CMOS devices consist of two different semiconductors, one for the p-channel and anoother for the n-channel. Numerous groups, however, have now demonstrated ambipolar transistors that present both n-channel and p-channel

In ambipolar OFETs both holes and electrons can be injected into semiconductor with energetically matched work function of metal contact with HOMO and LUMO level of semiconductor. To enhance injection of charge carriers, we used self-assembled monolayers (SAMs) which can control the work function in metal region.

In this work, we fabricated the ambipolar OFETs using material conjugated diketopyrrolopyrrole (DPP) unit as a semiconductor. The electrical characteristics of OFETs were measured with various bias conditions, annealing temperatures and SAMs treatment. We obtained μh=2 ?2V-1S-1 and μe= 0.2 ?2V-1S-1 at 300? without any SAMs treatment, respectively. And then inverter device was fabricated using one active layer and measured gain characteristics with different drain voltage. Gain of inverter was measured about 25.

9185-137, Session PWed

Stable operation of nonvolatile multistate memory using organic ferroelectric field-effect transistor circuits

Min-Hoi Kim, Jae-Hyun Lee, Hanbat National Univ. (Korea, Republic of)

Ferroelectric organic field-effect transistors (OFETs) have attracted much attention due to the potential for the nonvolatile data storage and design flexibility. Recently, for the massive data storage purpose, it is desirable that more than a single is stored at a single ferroelectric memory cell. However, due to the relatively less margin between output current values, the practical application of the ferroelectric multistate memory is limited. In this work, we demonstrate a stable operation of nonvolatile multistate memory using organic ferroelectric field-effect transistor circuits. The multistate memory cell is composed of a load ferroelectric organic field-effect transistor (OFET) and a driving paraelectric OFET for an zero-gate load inverter-type circuit geometry. For load ferroelectric OFET, the ferroelectric material, poly(vinylidene fluoride) copolymer with trifluoroethylene (75/25 mol %) copolymer, is used for a gate insulator. The states of a ferroelectric dipoles in the gate insulator is determined by varying the magnitude of the programming voltage, which allows the multilevels of the drain current in a load ferroelectric OFET. In the memory cell, the current-readable output from the ferroelectric load OFET is directly converted into the voltage-readable output in the ferroelectric inverter circuit. It is found that four memory states of ferroelectric memory cell is distinguishable at high temperature condition (70 oC) or in the elapsed state (48 h) due to the similar temperature-dependency and time-dependent degradation of two load and driving transistors. These similar tendencies of two transistors cancel out the effect of the

temperature-dependency and time-dependent degradation each other, resulting in the stable operation of the multistate memory cell.

9185-138, Session PWed

Tunable crystalline structures of diketopyrrolopyrrole (DPP)-based semiconducting polymers for high-performance organic field-effect transistors

Mi Jang, Hoichang Yang, Inha Univ. (Korea, Republic of)

Novel semiconducting polymers containing electron donors (D) and acceptors (A) were synthesized in order to improve the electrical properties of these solid forms in organic electric devices. Here, we prepared solution-processed copolymers with diketopyrrolopyrrole (DPP) acceptor and thiophene (or selenophene) donor groups. In addition, alkyl side-chain components were changed to optimize the solution-processability and directed self-assembly of these polymers during film processes. DPP-based semiconducting polymer films were solution-cast on hydroxyl free gate dielectrics (polymer grafted oxide dielectrics) from various solutions. Some of the cast films were further post-treated to improve these crystallinities and & #960;-conjugated orientations. Electrical properties of the cast DPP polymer films in organic field-effect transistors (OFETs) were characterized and correlated with the corresponding crystal structures, as determined by scanning probe microscopy (atomic force microscopy, AFM, for surface morphology), synchrotron-based grazing-incidence X-ray diffraction (GIXD, for crystalline structure and crystallinity), and near-edge X-ray absorption fine structure (NEXAFS, for orientation of pi-stacked plain).

9185-139, Session PWed

Polymer gated organic field effect transistor using magnesium phthalocyanine

Rajesh R. Kallarakkal, Oregon State Univ. (United States); C.S Menon, School of Pure and Applied Physics, Mahatma Gandhi University (India)

An organic thin film transistor has been fabricated using thermally evaporated Magnesium Phthalocyanine as active layer. The performance of OFETs such as operating voltage depends critically on gate dielectric materials and their interfacial properties because the dielectric surface contacts with the channel of OFETs, where drain current flows . The interactions between these surfaces and the deposited organic can have a profound effect on thin-film growth and the resulting electrical characteristics since most of the charge transport in these structures occurs near the organic-insulator interface.

We have used parylene – C as the Gate insulator, which can be deposited by Chemical Vapour Deposition (CVD) on the surface of ITO coated Glass at room temperature and can form a parylene/Organic interface with a low density of electronic defects . Parylene forms pin hole free, thin conformal transparent coatings with excellent dielectric and mechanical properties . It is passivated all the area on substrate except ITO contact areas. The application of the parylene CVD process to realize MgPc OFETs has not been reported before.

Parylene film prepared by chemical vapour deposition has been used as the organic gate insulator. Annealing of the samples is performed at 120degC for 3 hrs. We have determined the transistor parameters of the device at room temperature. Comparison of electrical properties of virgin and annealed devices provides an insight into the trap distributions. At room temperature, these transistors exhibit the p-type conductivity with field-effect mobility ranging from 0.009 - 0.021 cm2/Vs and (on/off) ratio ~ 10^3. The effect of annealing on the transistor characteristics is discussed.

9185-140, Session PWed

Electrical characteristic of IGZO Oxide TFTs with organic/inorganic gate dielectric insulator

Sang Chul Lim, Electronics and Telecommunications Research Institute (Korea, Republic of)

In this study, we applied the hybried gate dielectric layer to a-IGZO TFTs in order to display panel performance improvement, and also semiconductor active layer with protection layer (PL). The device fabrication process involves a series of thin film deposition and photolithographic patterning steps. The devices structure were fabricated top-contact gate TFTs using the a-IGZO films on the plastic substrates. The electrodes consisting of Ti(15 nm)/Al(120 nm)/Ti(15nm) trilayers were deposited by direct current sputtering. The 30 nm thickness active IGZO layer deposited by rf magnetron sputtering at room temperature. The deposition condition is as follows: a rf power 200 W, a pressure of 5 mtorr, 10 % of oxygen [O2/(O2+Ar)=0.1], and room temperature. A 9-nm-thick Al2O3 layer was formed as a first, third gate insulator by ALD deposition. A 290-nm-thick SS6908 organic dielectrics formed as second gate insulator by spin-coating. The drain current (IDS) versus drain-source voltage (VDS) output characteristics curve of a IGZO TFTs fabricated using the hybride gate dielectric layerr on a plastic substrate and log(IDS)-gate voltage (VG) characteristics for typical IGZO TFTs. The TFTs device has a channel width (W) of 80 μm and a channel length (L) of 20 μm. The IDS-VDS curves showed well-defined transistor characteristics with saturation effects at VG>-10 V and VDS>-20 V for the sputtering IGZO device. The charge carrier mobility was determined to be 15.18 cm2 V-1s-1 with FET threshold voltage of -3 V and on/off current ratio 109

9185-141, Session PWed

Top-gate polymer thin-film transistors fabricated on elastomeric substrates

Soon-Won Jung, Jeong Seon Choi, Chan Woo Park, Bock Soon Na, Sang Chul Lim, Sang-Seok Lee, Hye Yong Chu, Jae Bon Koo, Electronics and Telecommunications Research Institute (Korea, Republic of)

PDMS based electronic devices are widely used for various applications in large area electronics, biomedical wearable interfaces and implantable circuitry where flexibility and/or stretchability are required. A few fabrication methods of electronic devices directly on PDMS substrate have been reported. However, it is well known that micro-cracks appear in the metal layer and in the lithography pattern on a PDMS substrate. To solve the above problems, a few studies for fabrication of stiff platform on PDMS substrate have been reported. Thin-film islands of a stiff region are fabricated on an elastomeric substrate, and electronic devices are fabricated on these stiff islands. When the substrate is stretched, the deformation is mainly accommodated by the substrate, and the stiff islands and electronic devices experience relatively small strains. Here, we report a new method to achieve stiff islands structures on an elastomeric substrate, as the platform for stretchable electronic devices. The stiff islands were defined by conventional photolithography on a stress-free elastomeric substrate.

9185-142, Session PWed

Polyimide/silicon elastomer substrate for stretchable electronics

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Stretchable electronic system on elastomeric substrates is a new emerging class of electronics. In recent years, this field has gained widespread interest as stretchable circuits enable conformability of electronic systems to more complex shapes in comparison with conventional flexible systems. They allow for improved user comport and reliability by enhanced dynamical shaping and matched mechanical properties of the electronic system to its environment. To date, a various strategies towards the realization of stretchable electronic systems have been reported. One strategy, a supporting elastomeric substrate is first stretched, then circuit materials are deposited onto the pre-strained substrate, and finally releasing the pre-strain. This relaxation leads to the spontaneous formation of wrinkled wavy structures. However, basically this pre-strain wavy method is susceptible to reliability because it is difficult to precisely control the pre-strain over a very large substrate area. Here, we developed a new Polyimide(PI)/Polydimethylsiloxane(PDMS) hybrid stretchable substrates on the wavy silicon mold without pre-stretching. Thinned PI is spin-coated on the silicon wavy mold substrate and then thick rigid islands of PI is produced by conventional photolithography on the thin PI. Then, by casting PDMS and thin/thick islands of PI is transferred on the PDMS. In the repetitive stretching test, thick rigid islands area of PI is not deformed and only thin wavy membrane area is deformed.(at 70% applied overall tensile strain, membrane area showed more than 70% tensile strain) In this technique, we can provide various types of wavy profiles for stretchable substrates.

9185-143, Session PWed

Comparative study on degradation and trap density-of-states of p type and n type organic semiconductors

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Over the past twenty years, remarkable progresses have been made in organic thin film transistor (OTFT) by synthesising novel high performance organic semiconductors and optimising fabrication conditions. The organic semiconductors have possible applications in low-cost, large area and flexible devices. In the present study, a n-type organic thin film transistor (OTFT) with N,N?-Dioctyl-3,4,9,10-perylenedicarboximide (PTCDI-C8) as the n-channel layer was fabricated on Si/SiO2 substrate by thermal evaporation technique at a substrate temperature of 1200C. Thermally oxidized silicon wafer SiO2 of thickness 108nm was used as the gate dielectric. The OTFT staggered bottom gate structure was electrically characterized in vacuum (10-1 mbar) immediately after the device fabrication. Care had been taken to avoid light during the measurement in order to prevent the degradation of PTCDI-C8 layer. The device showed a field-effect mobility of 0.02 cm2/Vs, threshold voltage around 25.3 V, subthreshold swing of 0.73V/decade and an on/off ratio of 6.5x105. Perylene diimide derivatives are extensively used electron transport materials due to high electron affinity. It is expected that exposure of OTFT to light and air will make noticeable changes in the device properties which are currently being investigated.

9185-144, Session PWed

Development of inkjet-printed PMOS inverters on flexible substrate

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Inkjet printing is one of the promising methods for the fabrication of solution-processable electronics. Here, we present a comprehensive study on inkjet printing processes for the organic semiconductor, dielectric material and Ag electrodes in organic thin-film transistors (OTFT) fabrication. The manufacturing yield of 97% of inkjet-printed OTFTs has been demonstrated. Optimized enhancement-load PMOS inverters on PET substrate obtained a high voltage gain up to 11 v/v. The results demonstrated the potential of inkjet printing process for the fabrication of electronics on flexible substrate.

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9185-201, Session 1

Luminescent AIE materials for high-performance sensing applications *(Invited Paper)*

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Luminescent materials have been used for electronic, optical, chemo- and bio-sensing applications with high signal-to-background ratio, superior sensitivity and broad dynamic ranges. Traditional luminophores suffer from aggregation-caused quenching (ACQ) effect due to π–π stacking upon aggregate formation. The ACQ effect limits the scope of practical sensing applications.

A novel phenomenon named aggregation-induced emission (AIE) has been observed by our groups. Luminogens with AIE characteristics enjoy high emission efficiency in the solid or aggregate state while non-emissive when they are molecularly dissolved. AIE tackles the lethal problem of classic fluorescence materials in sensing applications. Silole and tetraphenylethene are the archetypal AIE cores and possess the advantages of facile synthesis and ready functionalization. They can be decorated with large variety of moieties for targeting different analytes.

AIE luminogens, including small molecules and big polymers, have been utilized to develop various optical sensors. Take explosive detection as an example, AIE polymers with different topologies can be used for detecting picric acid and 2,4,6-trinitrotoluene by quenching effect with high sensitivity and selectivity. The detections can be done in the form of solid and solution which facilitates practical usage. They can also be used as the sensors for volatile organic compounds and metal ions, such as mercury and zinc ion, through fluorescence turn-on mechanism.

AIE luminogens have also been successfully applied in the field of biology. Water-soluble AIE luminogens have been designed for biological sensing and imaging, for example, quantification of nucleic acids and proteins and real-time monitoring of their conformational changes. Some of them can not only quantify the target analytes but also follow the kinetics of conformational changes, making them promising for diagnostic and therapeutic applications. These demonstrations significantly expand the scope of analysis applications of AIE luminogens and offer new strategies to the design of new fluorescent sensors.

9185-202, Session 1

Selective detection of nitrated analytes *(Invited Paper)*

Paul L. Burn, Shengqiang Fan, Andrew Clulow, Paul Meredith, Paul E. Shaw, The Univ. of Queensland (Australia)

Detection of explosives can play an important role in combating terrorism and humanitarian de-mining in war-torn countries. Many detection systems used for identifying the presence of explosives are cumbersome or not portable. Luminescent conjugated polymers have been successfully used in portable detectors where the presence of the analyte is detected by a decrease in the luminescence. We have discovered that light-emitting dendrimers can also be used for effective detection of explosive analytes. Dendrimers are comprised of a core, dendrons (branched units), and surface groups, which are found at the distal ends of the dendrons. In this presentation we will describe our recent steps in designing dendrimers that can sense explosives, discuss the effect of the components within the dendrimer on sensing process. We will show that the nitrated analytes can be rapidly and selectively detected.

9185-203, Session 1

Correlating explosive analyte diffusion with fluorescence quenching in bifluorene-cored dendrimer thin films

Mohammad A. Ali, Paul E. Shaw, Ian R. Gentle, Paul L. Burn, The Univ. of Queensland (Australia)

Detection of explosives is crucial for security, military operations and environmental monitoring. Of the currently available detection methods, those based on photoluminescence (PL) quenching of a sensing film offer a plausible route to a light-weight portable detector. For the PL of the sensing film to be quenched the target analyte molecules have to be in close proximity with the sensing molecules. Therefore, how the analyte (explosive) molecules diffuse into the fluorescent sensing film and interact with the chromophores is of particular interest in order to design new sensing molecules that are both selective and sensitive towards the target analytes. In this presentation we will describe an in-situ custom-built cell comprised of a quartz crystal microbalance (QCM) and fluorescence spectrometer, and how it can be used to monitor mass and PL changes synchronously as the sorption proceeds. We will show that the sorption curves suggest that diffusion of p-nitrotoluene (pNT) into fluorescent dendrimer sensing films does not strictly obey Fick's law. The PL of the film drops quickly at the initial time of the sorption. We will use this data to discuss the importance of the ratio of the quenching analyte to the sensing compound for detectable changes in the PL. Finally, we will describe a distance-dependent quenching model that helps in understanding the photophysics of the quenching process.

9185-204, Session 1

Explosive vapor sensing by star-shaped molecules *(Invited Paper)*

Ifor D. W. Samuel, Yue Wang, Paulina Morawska, Univ. of St. Andrews (United Kingdom); Alexander Kanibolotsky, Univ. of Strathclyde (United Kingdom); Zarifi Masri, Arvydas Ruseckas, Univ. of St. Andrews (United Kingdom); Igor F. Perepichka, Bangor Univ. (United Kingdom); Peter J. Skabara, Univ. of Strathclyde (United Kingdom); Graham A. Turnbull, Univ. of St. Andrews (United Kingdom)

The detection of explosives is important for security and humanitarian demining. The vapour of many explosives quenches the fluorescence of conjugated molecules. This can be detected as a loss of fluorescence intensity, a shortening of fluorescence lifetime, or a change in the output of a laser made from the material. In this paper we explore the influence of molecular structure on explosive detection in a family of star-shaped molecules. The molecules consist of a truxene core to which three oligofluorene arms are attached, each consisting of two, three or four fluorene units. The influence of the length of the arms on explosive detection was measured. Exciton diffusion was also measured in these materials, and the implications for the sensing mechanism will be discussed.

9185-205, Session 2

Integrated sensors for point of care detection *(Invited Paper)*

John C. de Mello, Imperial College London (United Kingdom)

Microfluidic devices have shown themselves to be highly effective for laboratory-based research, where their superior analytical performance has established them as efficient tools for genetic sequencing, proteomics, and drug discovery. However to date they have not been well suited to point-of-care diagnostic applications, where cost and portability are of primary concern. Although the microfluidic chips themselves are cheap and small, they must generally be used in conjunction with bulky optical detectors, which are needed to identify or quantify the analytes or reagents present. Here we report the use of miniature on-chip light sources and photodetectors based on light-emitting polymers, together with a range of new low cost strategies for the sensitive detection of low concentration analytes.

9185-207, Session 2

Plasmonic interferometer arrays for high-performance label-free biomolecular sensing *(Invited Paper)*

Filbert J. Bartoli, Yongkang Gao, Beibei Zeng, Lehigh Univ. (United States); Qiaoqiang Gan, Univ. at Buffalo (United States); Xuanhong Chang, Lehigh Univ. (United States)

We investigate novel plasmonic interferometric biosensors that combine small (microscale) SPR sensor footprints with highly sensitive interferometric techniques. Arrays of circular aperture-groove nanostructures were patterned on a gold film for biomolecular detection, tailoring the phase and amplitude of interfering surface plasmon polaritons to decrease the plasmon linewidth. Narrow spectral interference fringes with high contrast were experimentally demonstrated, yielding a resolution of protein surface coverage as low as 0.4 pg/mm2. The simple, low-cost collinear transmission geometry is promising for fast, inexpensive, compact biomedical devices. Intensity interrogation methods were also employed to achieve record high nanoplasmonic sensing performance for high-throughput multiplexed sensing.

9185-208, Session 2

Selectivity and sensitivity enhancement of bulk heterojunction organic photodetectors *(Invited Paper)*

Kai Cheong Tam, Hoi Lam Tam, Kok-Wai Cheah, Furong Zhu, Hong Kong Baptist Univ. (Hong Kong, China)

Organic photodetectors (OPDs) have attracted a lot of interests due to their potential application in low cost, large area imaging devices and sensors. Organic materials with tailored electrical and desired spectral response are required for achieving high selectivity and sensitivity OPDs. In addition to the materials innovation, another key technical development to circumvent this hurdle is a device design to enhance light trapping at the preferred wavelength of interest, e.g., using optical microcavity effect to enhance the spectral selectivity and sensitivity of OPDs for a chosen material system. Optical microcavity allows tuning the spectral response of the devices, thereby enhancing the resonance quality and sensitivity of the cavity-based OPDs.

In this work, an enhancement in sensitivity of solution-processed bulk heterojunction OPDs, based on the blend of regio-regular poly(3-hexylthiophene): [6,6]-phenyl-C61-butyric acid methyl ester, is realized using an internal optical microcavity configuration. The selectivity and sensitivity of microcavity OPDs at the desired wavelength can be augmented by tuning the cavity length. It is found that the sensitivity of cavity-based OPDs is >8 times efficient than a control regular organic photodetector, having an identical device configuration without a cavity configuration. Frequency response and optical selectivity of the cavity-based OPDs were analyzed.

9185-212, Session 2

OLED micro-displays as biophotonic platform *(Invited Paper)*

Malte C. Gather, Univ. of St. Andrews (United Kingdom)

Microdisplays based on organic light-emitting diodes (OLEDs) are a novel type of display with primary applications in viewfinders and wearable glasses. They typically comprise of a silicon chip containing the electronics to individually address >10^5 top-emitting OLED pixels deposited directly on the chip. Here, we discuss the prospect of using OLED microdisplays as platform for advanced cell biology. The displays have a size of a few millimeters and each pixel has dimensions in the range of several micrometers; small enough to resolve, address and interface parts of individual live cells with each pixel of the microdisplay.

9185-206, Session 3

Conjugated polymer nano-probes for tumor imaging and theranostics

Alexander J. C. Kuehne, DWI an der RWTH Aachen e.V. (Germany); Wiltrud Lederle, RWTH Aachen (Germany)

Conjugated polymer particles exhibit broad optical absorption and are tunable in their emission wavelength. By contrast to inorganic quantum-dots, conjugated polymers are non-cytotoxic and hence present an ideal material system for application in the biomedical field. However, current conjugated polymer systems rely on non- or insufficiently functionalized particles with broad size distributions. Endocytosis, the process by which fluorescent particles are usually internalized by cells, is highly size dependent, which may lead to poor contrast in cell imaging when polydisperse particles are applied. Here I will present the synthesis of monodisperse conjugated polymer particles via Sonogashira coupling, which allows subsequent selective coupling of biologically relevant molecular epitopes by thiol-yne click-reaction. RGD-peptide sequences allow for targeting of integrins which are over-expressed in the tumor endothelium. RGD functionalized conjugated polymer particles bind to HUVEC cells and can hence be applied to selectively stain the vascularization of tumors, which will allow surgeons to differentiate healthy from cancerous tissue and eventually allow for non-invasive cancer diagnosis and more conservative therapy.

9185-209, Session 3

Improved charge injection in opto-electronic devices by incorporating DNA interlayer *(Invited Paper)*

Thuc-Quyen Nguyen, Univ. of California, Santa Barbara (United States)

Charge injection barriers can often be found at electrode-organic semiconductor interfaces. These interfaces play a key role in determining device characteristics and performance. For example, in polymer light-emitting diodes (PLEDs), these barriers can cause imbalanced electron and hole densities and therefore lower the device efficiency. In organic field-effect transistors (OFETs), energetic barriers can determine device parameters such as turn-on voltage, on-off ratios, high contact resistance, and even enable observation of bipolar behavior. I will discuss the potential application of DNA as an interlayer to improve charge injection in PLEDs, n-type OFETs, and ambipolar OFETs. Incorporation of DNA interlayers leads to improvements in the transport of PC70BM and ambipolar transport in diketopyrrolopyrrole (DPP)-based OFETs. We attribute these observations to improved charge injection at the Au/organic interface. The field-effect mobility for PC70BM and DPP devices is enhanced together with a reduced contact resistance. For PLEDs, electron injection is improved using a thin layer of DNA between the emissive layer and the Al cathode. The DNA interlayer significantly

lowers the device turn-on voltage and increases the luminance efficiency. For organic phototransistors, incorporating a thin DNA layer leads to a two-order enhancement of the photoresponse with a photosensitivity exceeding 103. These examples demonstrate unique potential applications of biomolecules in organic optoelectronics for various applications.

9185-210, Session 3

Organic sensor systems fabricated by hybrid lithography comprising UV-exposure and two photon direct laser writing

Uli Lemmer, Carsten Eschenbaum, Siegfried W. Kettlitz, Sebastian Valouch, Karlsruher Institut für Technologie (Germany)

Optofluidic systems based on active organic semiconductor devices require the integration of passive optical components for controlling light propagation. We have developed a method for three dimensional alignment of patterns fabricated by a combination of conventional UV-lithography and two photon polymerization direct laser writing (2PP-DLW). The resist used for UV-lithography is doped with a fluorescent dye. After developing the structures and covering with a conventional resist, the doped structures could be identified through the contrast in fluorescence intensity. After UV-lithography of the larger structure, an aligned 2PP-DLW step allows to fabricate small 3D structures on or adjacent to the large structures. This hybrid lithography method is capable for the fabrication of complex 3D masters for different replication techniques in the field of microfluidics, photonics and MEMS. In particular, photonic application might require a subsequent replication by nano imprint lithography or hot embossing to avoid fluorescence of the dye. This method allows for easy and fast fabrication of large scale lithographic structures in combination with nano-scale and/or 3D structures. As a proof of concept, a master for soft-lithography was produced, which consists of a microfluidic-system in combination with a TIR-mirror [1]. This optofluidic system enables three dimensional particle tracking inside a microfluidic channel using organic photodiodes.

[1] C. Eschenbaum, D. Großmann, K. Dopf, S. Kettlitz, T. Bocksrocker, S. Valouch, U. Lemmer, Opt. Expr. 21 29921 (2013).

9185-211, Session 3

Conformable wearable systems comprising organic electronics on foil for well being and healthcare

Margreet M. de Kok, Holst Ctr. (Netherlands)

Conformable wearable systems comprising organic electronics for healthcare and well being

Margreet M. de Kok, Gert van Heck, Adri van de Waal, Ahmed Salem, Marc Koetse, Jeroen Schram, Jeroen van den Brand

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Integration of electronics into materials and objects that have not been functionalized with electronics before, open up extensive possibilities to support mankind. By adding intelligence and/or operating power to materials in close skin contact like clothing, furniture or bandages the health of people can be monitored or even improved. Foil based electronics are interesting components to be integrated as they are thin, large area and cost effective available components Our developed technology of printed electronic structures to which components are reliably bonded, fulfills the promise. We have integrated these components into textiles and built wearable encapsulated products with foil based electronics.

Foil components with organic and inorganic LEDs are interconnected and laminated onto electronic textiles by using conductive adhesives to bond the contact pads of the component to conductive yarns in the textile. Modelling and reliability testing under dynamic circumstances provided important insights in order to optimise the technology. The design of the interconnection and choice of conductive adhesive / underfill and lamination contributed to the durability of the system. Transition zones from laminated foil to textile are engineered to withstand dynamic use.

As an example of a product, we have realized an electronic wristband that is encapsulated in rubber and has a number of sensor functionalities integrated on stretchable electronic circuits based on Cu and Ag. The encapsulation with silicone or polyurethanes was performed such, that charging and sensor/skin contacts are possible while simultaneously protecting the electronics from mechanical and environmental stresses.

9185-213, Session 3

Recent developments in the OLED-based platform for analytical applications *(Invited Paper)*

Joseph Shinar, Weipan Cui, Eeshita Manna, Rui Liu, Ruth Shinar, Iowa State Univ. (United States)

We will describe the effect of relative humidity (RH) on oxygen monitoring using the OLED-based sensing platform. This effect is strongly dependent on the matrix of the sensing probe. Porous matrices, and in particular titania-doped ethyl cellulose, enable differentiation of 10% changes in RH. We will also describe the development of an on-chip OLED-based spectrophotometer with an expanded range of ~360 nm to 650 nm. The spectrophotometer is based on combinatorially-fabricated microcavity OLED pixels. In these pixels the peak emission wavelength is determined by the emitting material, whether 4,4?-Bis(N-carbazolyl)-1,1?-biphenyl (CBP), Bis[2-(4,6-difluorophenyl)pyridinato-C2,N](picolinato) iridium(III) (FIrpic), Ir(III)[tris2-4-tolylpyridinato-N, C2] (Ir(mppy)3), Iridium (III) bis(2-methyldibenzo[f,h]quinoxaline) (acetylacetonate) (Ir(MDQ)2(acac)), or Pt octaethyl porphyrin (PtOEP), and the thickness of the MoOx hole injection layer and the BPhen electron transporting layer.

9185-214, Session 4

Recent progress in up-conversion devices *(Invited Paper)*

Do Young Kim, Tzung-Han Lai, Jaewoong Lee, Jesse R. Manders, Franky So, Univ. of Florida (United States)

Optical up-conversion devices have been studied in the last two decades as an alternative technology for near-infrared (IR) imaging. However, fabrication of IR-to-visible up-conversion devices based on inorganic compound semiconductors is challenging because of the lattice mismatch between the two types of semiconductor materials used for photodetectors and light emitting diodes. Because of the high costs of epitaxial grown inorganic devices, these devices are only suitable for small area applications. Recently, optoelectronic devices based on organic materials have received a lot of attention because of their compatibility with large area manufacturing. Also, solution-processed inorganic nano-materials such as PbS quantum dots (QDs) have attracted a great deal of attention because of their potential for low cost IR sensitizing materials. Here, we report on low cost IR-to-visible up-conversion devices with organic light emitting diodes (OLEDs) and colloidal PbS QDs as a visible emitter and an IR sensitizing layer, respectively. The up-conversion devices have a similar structure compared with conventional OLEDs. The key to up-conversion device is to keep the device in the off-state even if a forward bias is applied to it and to turn-on the device only when there is incident IR light. The up-conversion device responds to IR irradiation with wavelength up to 1500 nm. Finally, we demonstrated red, green and blue emitting up-conversion devices.

9185-215, Session 4

Fabrication of an X-Ray detector based on molecular plastic electronics

Beynor A. Paez-Sierra, Pontificia Univ. Javeriana Bogotá (Colombia) and QUBITeXp International Trade S.A.S. (Colombia); Hernán Rodríguez, Juan M. Sánchez, Miguel A. Rodríguez, Leon D. Pérez, Pontificia Univ. Javeriana Bogotá (Colombia)

We present an organic X-ray detector with an active layer deposited from a novel semiconducting ink formulation. The precursor ink consist of blended poly(3-hexylthiophene-2,5-diyl) (P3HT), phenyl-C61-butyric acid methyl ester (PCBM) and the organometallic nanostructure copper(II) 2,2'-bipyridine (Cu(II)(bpy)).

The use of ligands like 2,2' byripidine with cationic species such as Cu(II) improves their solubility in organic solvents. The purpose of the organometallic complex Cu(II)bpy is twofold: to achieve a homogeneous semiconducting ink with P3HT:PCBM blends and to enhance the X-ray interaction with the organic layer through the Cu(II) cation.

Our X-ray displays consist of several pixels, each with vertical structures comprising a bendable PET/ITO substrate with a spin-coated semiconducting ink of P3HT:PCBM:Cu(II)bpy (60 nm), followed by thermal evaporation of Al (100 nm) contacts.

In order to test the devices, each pixel is exposed to X-ray energies ranging from 0 keV to 35 keV.

To the best of our knowledge, this is the first example where an organic X-ray detector includes the organometallic complex Cu(II)bpy in P3HT:PCBM blends, and the electrical characterization of the detector is carried out by impedance spectroscopy (IE).

The reported organic X-ray detectors probed by IE have revealed to be linear dependent with X-ray energy, and more sensitive compared with standard photocurrent-voltage characteristics. Impedance spectra are recorded at frequencies between 20 Hz and 20 kHz and at a modulating signal of 50 mV. The measurements are interpreted with microscopic model calculations for the impedance bands.

9185-216, Session 4

Charge trap engineering for highly sensitive photodetectors *(Invited Paper)*

Jinsong Huang, Univ. of Nebraska-Lincoln (United States)

High sensitivity photodetectors in ultraviolet (UV) and infrared (IR) range have broad civilian and military applications. We report on an un-cooled solution-processed UV-IR photon counter based on modified organic field-effect transistors. This type of UV detectors have light absorbing zinc oxide or lead sulfide nanoparticles (NPs) sandwiched between two gate dielectric layers as a floating gate. The photon-generated charges on the floating gate cause high resistance regions in the transistor channel and tune the source-drain output current. This "super-float-gating" mechanism enables very high sensitivity photodetectors with a minimum detectable ultraviolet light intensity of 2.6 photons/μm2s at room temperature as well as photon counting capability. Based on same mechansim, infrared photodetectors with lead sulfide NPs as light absorbing materials have also been demonstrated.

9185-217, Session 4

Green alternatives for sustainable organic electronics: H-bonded organic semiconductors *(Invited Paper)*

Eric D. Glowacki, Johannes Kepler Univ. Linz (Austria); Mihai Irimia-Vladu, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria)

Organic electronics has a tremendous potential for the development of electronic products that are non-toxic and environmentally friendly biodegradable. An ideal solution is the production of such devices either from naturally occurring or from nature-inspired materials that have been proved to be biodegradable and biocompatible as well as processible from aqueous or benign solvents. This presentation will highlight the emerging class of natural materials and their usage in organic electronics as substrates, dielectrics, smoothening layers and semiconductors, and will focus preponderantly on the emerging family of natural and nature-inspired hydrogen bonded semiconductors.

In nature, many pigments are hydrogen-bonded small molecules as opposed to larger, van der Waals bonded synthetic molecules like pentacene, phthalocyanines or oligothiophenes. Interestingly, many of such pigments demonstrate H-bonding as well as p-stacking. The strong electronic coupling afforded by H-bonding yielded optical properties controlled by intermolecular interactions. Among the materials we have exploited are naturally-occurring indigo, Tyrian Purple and acridone, together with a large family of synthetically produced indigoid, anthraquinone and acridone derivatives, many of them widely exploited as non-toxic cosmetic or food colours. When processed in thin films, they generate extensive long-range ordered structures with crystalline textures showing a single preferential orientation, unlike the typical herringbone pattern found in many van der Waals bonded semiconductors. We implemented air-stable unipolar and ambipolar H-bonded, natural or nature-inspired semiconductor materials in organic field effect transistors and various types of integrated circuits, where field-effect mobilities in excess of 1 cm2/Vs were recorded. We found also excellent stability to degradation of those devices and excellent charge transport in air during testing periods of several months.

Nature inspires us to choose among a wide range of diverse materials for creating new electronic functionalities, coming closer to a vision of a sustainable electronics world.

9185-401, Session Plen

Materials and Devices for Bioresorbable Electronics

John A. Rogers, Univ. of Illinois at Urbana-Champaign (United States)

A remarkable feature of the modern integrated circuit is its ability to operate in a stable fashion, with almost perfect reliability. Recently developed classes of electronic materials create an opportunity to engineer the opposite outcome, in the form of devices that dissolve completely in water, with harmless end products. The enabled applications range from 'green' consumer electronics to bio-resorbable medical implants—none of which would be possible with technologies that exist today. This talk summarizes recent work on this physically 'transient' type of electronics, from basic advances in materials chemistry, to fundamental studies of dissolution reactions, to engineering development of complete sets of device components, sensors, and integrated systems. An 'electroceutical' bacteriocide designed for treatment of surgical site infections provides an application example.

9185-218, Session 5

Large area fabrication of self-aligned flexible organic thin film transistors using roll-to-roll compatible nanoimprint- lithography with natural and nature-inspired materials for biocompatible and biodegradable electronics *(Invited Paper)*

Andreas Petritz, Alexander Fian, Mihai Irimia-Vladu, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria); Archim Wolfberger, Montan Univ. Leoben (Austria); Ursula Palfinger, Anja Haase, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria); Thomas Griesser, Montan Univ. Leoben (Austria); Barbara Stadlober, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria)

One of the main prerequisites to promote industrial commercialization of organic electronics is to improve the switching speed of organic transistors which is rather low compared to its inorganic counterpart. One approach to improve the performance is downscaling. However, downscaling of oTFTs is challenging: the key issue is the miniaturization of all critical layers and feature sizes, such as gate dielectric thickness, channel length and electrode overlap . A self-alignment process as developed by us is a very promising technique to fulfill these requirements. In a first step a gate electrode is structured by photolithography or nanoimprint lithography for submicron features. After the deposition of an ultrathin dielectric layer the source/drain-electrodes are defined by back-substrate exposure of a photoresist through the nanoscaled gate electrode acting as the photomask in the transistor channel. This self-aligned architecture provides channel lengths in the sub-µm range with minimized geometric overlap down to several 10 nm and therefore reduces the parasitic gate capacitance which is one of the main limiting factors to fabricate fast oTFTs.

Natural or nature-inspired dielectric and semiconducting materials have been recently successfully implemented in organic field effect transistors, and afforded performances on par with state-of-the-art synthetic organic materials. Among the materials we have exploited are naturally-occurring compounds like cellulose, shellac, nucleic bases, various sugars, natural gums and waxes, indigo and Tyrian purple, anthraquinone and acridone derivatives, to name a few. We have demonstrated fully-biodegradable devices and circuits featuring natural substrates, dielectric and semiconducting layers and showed that the successful implementation these novel class of 'green' technologies to self-aligned fabricated organic thin film transistors can be a suitable approach for large area flexible biocompatible and biodegradable organic electronics.

9185-219, Session 5

High performance biosensors based on solution-gated transistors with functionalized gate electrodes *(Invited Paper)*

Feng Yan, The Hong Kong Polytechnic Univ. (Hong Kong, China)

Solution-gated transistors have shown promising applications in biosensors due to the high sensitivity, low working voltage and the simple design of the devices. Solution-gated transistors normal have no gate dielectric and the gate voltages are applied directly on the solid/electrolyte interfaces or electric double layers near the channel and the gate, which lead to very low working voltages (about 1 V) of the transistors. On the other hand, the devices can be easily prepared by solution process or other convenient methods because of the much simpler device structure compared with that of a conventional field effect transistor with several layers. Many biosensors can be developed based on the detection of potential changes across solid/electrolyte interfaces induced by electrochemical reactions or interactions. The devices normally can show high sensitivity due to the inherent amplification function of the transistors. Here, I will introduce several types of biosensors studied by our group recently, including DNA, glucose, dopamine, uric acid, cell, and bacteria sensors, based on solution-gated organic electrochemical transistors or graphene transistors. The biosensors show high sensitivity and selectivity when the devices are modified with functional nano-materials (e.g. graphene, Pt nanoparticles) and biomaterials (e.g. enzyme, antibody, DNA) on the gate electrodes or the channel. Furthermore, the devices are miniaturized successfully for the applications as sensing arrays. It is expected that the solution-gated transistors will find more important applications in the future.

9185-220, Session 5

Electrolyte-gated organic field-effect transistors for ion and pH sensing applications *(Invited Paper)*

Emil J. W. List-Kratochvil, Technische Univ. Graz (Austria) and NanoTecCenter Weiz Forschungsgesellschaft mbH (Austria)

For the emerging fields of biomedical diagnostics and environmental monitoring, where sensor platforms for in-situ sensing of ions and biological substances in appropriate aqueous media are required, electrolyte-gated organic field-effect transistors (EGOFETs) seem to be the transducers of choice. Due to the formation of an electric double layer at the electrolyte/organic semiconductor interface, they exhibit a very high capacitance allowing for low-voltage and water-stable operation. In combination with the outstanding properties of organic devices like biocompatibility, low-temperature processability on flexible substrates, as well as the possibility to tune the physical and chemical properties enhancing the selectivity and sensitivity, EGOFET-based sensors are a highly promising novel sensor technology. In this context the realization of the first ion-selective EGOFETs as well as the realization as a broad range pH-sensor is discussed.

In this context the device characteristics of poly(3-hexylthiophene) (P3HT) – based EGOFETs for various substrates using water with different concentrations of NaCl as an electrolyte and various gate electrode materials, are presented. In order to obtain a sensitive as well as selective response to sodium a commercial available ion selective membrane was introduced. This novel potentiometric sensor showed a sensitive linear response for a broad detection range between 10-6 M and 10-1 M Na+ and a selective as well as reversible response without a complex recovering process was achieved. Moreover we will show the basic characterization of the corresponding ion selective membrane and discuss the limiting factors for a proper combination with an EGOFET for realizing a broad range pH-sensor based on an EGOFET. Besides presenting the general selective sensing mechanism of ISMs, the optimization as well as the fabrication of a new pH sensitive ISM will be presented. On the way to a pH-sensor for a broad detection range (pH 2 – pH 12) the challenges faced considering interfering ions and large membrane potential changes will be discussed.

9185-221, Session 5

Stable organic-based label-free chemical and biological sensors for aqueous environments

Minseong Yun, Canek Fuentes-Hernandez, Asha Sharma, Do Kyung Hwang, Amir Dindar, Sanjeev Singh, Sangmoo Choi, Bernard Kippelen, Georgia Institute of Technology (United States)

Low-cost, light-weight portable and reusable sensors are increasingly important as portable electronic products are enabling in-situ environmental monitoring and medical diagnostics using consumer electronic platforms. Monitoring of chemical and biologically relevant agents will require sensors with stable operation in air and/or in aqueous environments (i.e. inside the human body).

We report on a novel organic field-effect transistor (OFET) –based chemical and biological sensor geometry with stable operation in aqueous media. OFETs with a top-gate geometry having a bilayer gate dielectric and a porous metallic gate lead to sensors with fast, stable and repeatable label-free detection of chemical and biologically relevant molecules. These OFET-based sensors primarily respond by rapidly shifting their threshold voltage; making them very sensitive to diffused charged species or to species that change the electrostatic potential in the vicinity of the sensor. In contrast to previous approaches, our approach avoids intimate contact between the organic semiconductor channel and the analyte, leading to sensors wherein the electronic transduction arises from changes of the threshold voltage instead of combined changes of the charge mobility, off-current and threshold voltage values. A detailed characterization of the sensor operation in aqueous environments will be given and potential applications discussed. This novel OFET-based sensing geometry represents one step forward towards the realization of low-cost, portable, and reusable sensors for in-situ sensing of chemical and biological molecules.

9185-222, Session 6

Artificial protonic synapses with memory *(Invited Paper)*

Marco Rolandi, Univ. of Washington (United States)

In Asimov's "I, Robot", robots have positronic brains that use positrons – electron antiparticles – for learning, memory, and conscience. Since Asimov's 1940s novels, the quest for artificial intelligence is a central theme of science fiction and at the forefront of technological innovation. Transistors and integrated circuits in modern computers use electrons, less elusive than positrons, for information processing. In contrast, natural systems like the brain rely on chemical neurotransmitters and ions to communicate information across synapses between neurons. In the human brain, 1015 synapses process 100 times more operations per second than the IBM Blue Gene supercomputer using as little power as a smartphone. Learning and memory are achieved with regulation of the synaptic signal strength from past synaptic events. Here, we introduce fully ionic synaptic devices in which protons provide both memory and the output signal. These devices exhibit reversible short-term depression, and can be turned "on" and "off" with less than 50 fJ of energy per operation when appropriately miniaturized.

9185-223, Session 6

Effects of device geometry on the switching speeds of organic electrochemical transistors

Jacob Friedlein, Robert R. McLeod, Sean E. Shaheen, Univ. of Colorado at Boulder (United States)

It has been demonstrated that the redox switching of PEDOT:PSS can be used as the basis for the modulation of channel current in organic electrochemical transistors. In this work, we examine how treating the top surface of the PEDOT:PSS film before electrolyte deposition affects device switching speed. Altering this interface is expected to greatly impact device performance because of the barrier it presents to ion transport into the transistor channel. In particular, we examine the effects of solvent rinsing, oxygen plasma etching, and acid vapor annealing on the switching speed, ON/OFF ratio, and lifetime of devices. We consider how these treatments alter both the bulk and surface properties of the PEDOT:PSS films, such as modulus, phase segregation, and surface roughness. The devices consist of photolithographically patterned gold electrodes and PEDOT:PSS channels. Both solid state and liquid electrolytes are examined, as well as which post-deposition treatment is most effective in each case. In addition to optimizing the post-deposition treatments for maximum switching speed, we also use atomic force microscopy to examine the effects of these treatments on the morphology of the underlying PEDOT:PSS film. Finally, we will characterize the effect of post-deposition treatments on device lifetime. Because the flow of solvated ions into and out of the transistor channel causes swelling of the PEDOT:PSS, device lifetime is highly sensitive to the mechanical properties of the film. Therefore, a better understanding of methods for altering the film's mechanical properties and how these alterations effect device lifetime is essential for engineering stable devices.

9185-224, Session 6

Organic transistor-based wireless sensor system for biomedical applications *(Invited Paper)*

Tsuyoshi Sekitani, The Univ. of Tokyo (Japan)

We developed a wireless, flexible sensor system with organic transistors for use in biomedical applications. When the electrodes directly come into contact with wet human skin, electrostatic discharge is generated, thus damaging the device. Therefore, in order to use an organic sensor sheet in biomedical applications, we integrated organic electrostatic discharge (ESD) protection circuits with organic Schottky diodes. ESD protection circuits with organic Schottky diodes using copper phthalocyanine can achieve 2-kV ESD tolerance.

An organic circuit (ESD protection circuit and sensor system) was fabricated directly on a 12.5-mm-thick flexible polyimide substrate. The ESD protection circuit was fabricated using an organic Schottky diode. The sensor system was fabricated using a ring oscillator circuit with a pseudo-CMOS layout comprising four p-channel organic transistors. The flexible, p-type channel was formed using dinaphtho[2,3-b:2?,3?-f]thieno[3,2-b]thiophene (DNTT), and the gate dielectrics were formed with 70-nm-thick parylene through chemical vapor deposition. A 1-mm-thick parylene layer was deposited on the organic circuits to serve as a passivation layer against oxygen diffusion, humidity, and mechanical attrition. The mobility of the DNTT transistors exceeded 1 cm2/Vs at 8 V.

Power is wirelessly transmitted between coils through magnetic resonance at 13.56 MHz. In this study, we use magnetic resonance to increase the distance between flexible coils, instead of conventional electromagnetic induction. This sensor system can detect the change in resistance between two electrodes by measuring the frequency of an RC ring oscillator.

9185-225, Session 6

An implantable system for brain blood flow monitoring *(Invited Paper)*

Youngwan Kim, Amrita V. Masurkar, Columbia Univ. (United States); Hongtao Ma, Weill Cornell Medical College (United States); Ioannis Kymissis, Columbia Univ. (United States)

About 20% of patients suffering from epilepsy are candidates for surgical treatment through resection of the epileptic focus. There is a need to better identify the source of epileptic seizures to target the surgery to the correct area of the brain. Blood flow patterns in the brain are a more sensitive, rapid, and localized measure of abnormal activity in the brain associated with epileptic seizures than measures of electrical activity. Measurement of the blood flow through optical reflectometry therefore offers the opportunity to improve site localization beyond the current standard of care.

Current attempts to identify the seizure focus optically have used either transcranial measurements (which are obscured by the bone of the skull) or suspended cameras, which can only be used during surgery. We have been developing a series of thin and mechanically flexible, subcranially implantable monitoring systems that are capable of measuring the blood flow through optical reflectometry and identify the seizure focus. A series of monitors has been developed, the latest version of which uses organic light emitting diodes and organic photodetectors arrayed on a 20um thick sheet. The system, its structure, and results on phantoms and animal models will be discussed in this presentation.

9185-226, Session PWed

Extending detection range of mercury sensor based on inhibitor effect

Van Sang Le, Boram Kim, Han Young Woo, Pusan National Univ. (Korea, Republic of)

Base on that mercury ions (Hg2+) can interact with thymine (T) to form (T-Hg-T), which is stable than T-A Watson Crick base pair. By designing single-strand DNA (ssDNA) containing thymine groups, the hairpin structure can be easily formed in the presence of mercury ions. Many previous studies have reported mercury assays with high sensitivity and selectivity using this strategy. Here we designed a new detection scheme to extend the range of mercury detection using inhibitors such as complementary DNA (cDNA), conjugated polyelectrolytes (CPE) and iodide ions(I-). In the presence of cDNA, the binding interactions between ssDNA and Hg2+, and between ssDNA and cDNA will compete. A cationic CPE, FPQ-Br, will hamper the formation of the hairpin structure (via T-Hg-T formation) due to the electrostatic interaction between FPQ-Br and ssDNA. Moreover, the iodide ions also have strong binding affinity to mercury ions. Upon addition of the above inhibitors, the detection range of mercury ions was successfully controlled, which is important for realization of practical sensors with high detection sensitivity and selectivity.

9185-227, Session PWed

Interface formation between pentacene and silver contacts investigated by surface-enhanced Raman spectroscopy

Beynor A. Paez-Sierra, Pontificia Univ. Javeriana Bogotá (Colombia) and QUBITeXp International Trade S.A.S. (Colombia)

Interface formation between organic semiconductors and substrates or electrodes is of great interest to develop functional devices. In this paper we discuss on the interface formation between the organic semiconductor pentacene and silver as the top electrode. Pentacene is commonly used as active layer in organic field-effect transistors (OFETs). It is known that in OFEts significant percentage of the drain current is realized at organic layer thickness below 5 nm. Therefore, understanding the monolayer regime is vital to identify the physics and chemistry of the organic semiconductor.

We report in-situ Raman spectroscopy measurements of 1.5 nm pentacene films deposited under ultra high vacuum conditions onto Au or SiO2 and covered by several evaporations of silver atoms. In order to achieve a detailed molecular identity upon metal evaporation, Raman spectra at each evaporation stage was recorded. Analysis proved that a bare 1.5 nm pentacene film on smooth Au substrates reflects significant enhancement of the Raman signal.

For silver coverage below 0.4 nm thickness, the metal is still in its molecular state, with absence of enhancement of the Raman intensity. This contrasts with thicker silver layers. The latter case promotes enhancement of the Raman internal vibrational modes along the activation of normally infrared-active modes, and the enhancement factors are estimated to be close to 100. The in situ Raman spectroscopy measurements indicate absence of metallorganic pentacene-Ag complexes regardless of the substrate. This is in agreement with previous reports from XPS analysis

9185-228, Session PWed

Development of the PEDOT:PSS based pressure sensing devices

Ashok K. Batra, Alabama A&M Univ. (United States); Ashwith K. Chilvery, Talladega College (United States); Al-Muatasim Alomari, Manmohan D. Aggarwal, Alabama A&M Univ. (United States)

Studies on the electronic properties and applications of organic semiconductors have been of increasing interest in recent years. Organic materials are attractive due to their low cost, the ability to tailor their properties and to integrate them with inorganic semiconductors.Poly(3, 4-ethylenedioxythiophene): poly(styrene sulfonic acid) (PEDOT:PSS) is one of the most successful organic conductive materials due to its interesting physical and chemical properties. In the present work, we developed a low cost Brush-Coating technique to fabricate thin films of PEDOT:PSS on glass and flexible substrates. We studied the films of PEDOT:PSS and PEDOT:PSS + Pentacene and others for electronic and piezoresistive properties. The preliminary investigations show the attractive results for use in stress/strain sensing devices and will be presented

9185-229, Session PWed

PbS colloidal quantum dots IR photodetectors with trap-assisted photocurrent amplification

Jaewoong Lee, Do Young Kim, Franky So, Univ. of Florida (United States)

Infrared (IR) photodetectors have attracted a great deal of interest due to the their commercial as well as security applications. However, conventional infrared photodetectors have limited applications because of the high costs of epitaxial grown inorganic semiconductors. Here, we report on low cost, high gain and fast response IR photodetectors. PbS QDs were chosen as the IR sensitizing material because their optical absorption can be tuned from 0.7 µm to 2.4 µm. Cross-linked PbS nanocrystal thin films were fabricated with a sequential layer-by-layer spin-casting method. Using a hole blocking layer (HBL) and an electron blocking layer (EBL), the dark current is substantially reduced. The resulting solution processed photodetectors have an IR sensitivity up to 1500 nm with a gain of 155, a detectivity of 7.0?10^13 Jones, and a response time of 3.1 ms. The gain in the photodetector is due to the enhancement in an electron injection tunneling through the EBL under IR illumination. While photogenerated electrons are easily swept away through the electron transporting layers, photogenerated holes are captured in the trap sites. Accumulation of the trapped holes builds up a high electric field at the interface and further distorts the electron injection barriers, finally, resulting in electron tunneling through the barrier from the top electrode. This approach for the low cost and high performance IR photodetectors has wide applicability to all sorts of existing applications in IR light detection and also has great potential to new applications.

9185-230, Session PWed

Improved sensing probes for monitoring dissolved O2, gas-phase O2, and relative humidity

Weipan Cui, Rui Liu, Joseph Shinar, Ruth Shinar, Iowa State Univ. (United States)

We describe improved sensing probes for monitoring dissolved oxygen, as well as gas-phase O2 and relative humidity (RH). These probes are integrated with LED or OLED excitation, and in some examples with small-molecule or polymer organic photodetectors. Enhanced analyte-dependent photoluminescence (PL) signals are achieved by using nanoparticle-doped or porous blend films. Examples include polystyrene (PS) doped with TiO2 nanoparticles, and polyethylene glycol (PEG) blended with PS or with ethyl cellulose (EC). Washing away the water-soluble PEG in the blend films affects their attributes, generating voids in PS and EC, which, via light scattering, result in significantly increased PL signals.

9185-231, Session PWed

An in-ear microphone based on organic piezoelectric polymers

Andxy L. Zhang, Elizabeth Olsen, Ioannis Kymissis, Columbia Univ. (United States)

Organic piezoelectric materials offer a number of advantages in the fabrication of sensitive miniature microphone systems. Materials, such as PVDF and PVDF-TrFE co-polymers offer a low-durometer, mechanically flexible format, and an good acoustic impedance match with water.

Building on our development of an active matrix array microphone system, we have developed a series of in-ear implantable microphones based on the organic piezoelectric materials, and have also demonstrated the use of local amplification via instrumentation of the microphones with organic field effect transistors coupled to the piezoelectric layers. This presentation will detail several recent developments in the program, including the demonstration of in-cochlea sound measurement in a hamster model.

Conference 9186: Fifty Years of Optical Sciences at The University of Arizona

Tuesday - Wednesday 19–20 August 2014

Part of Proceedings of SPIE Vol. 9186 Fifty Years of Optical Sciences at The University of Arizona

9186-1, Session 1

Optical Sciences Center/College of Optical Sciences: fifty years of excellence *(Keynote Presentation)*

James C. Wyant, College of Optical Sciences, The Univ. of Arizona (United States)

The College of Optical Sciences, formerly known as the Optical Sciences Center (OSC), was established at the University of Arizona by Aden Meinel in 1964 to fulfill a national need for more highly trained engineers and physicists in the optical sciences. Throughout its 50-year history, OSC has grown and evolved in response to changing national needs and now includes a world-class faculty, an international student body, an undergraduate optical sciences and engineering degree program, and an outstanding MS and PhD graduate program that also includes a distance learning program for students who are unable to be full-time on-campus students. In response to strong industrial demand, the academic program has expanded to include more than 100 graduate and undergraduate level courses. OSC graduates are in great demand and are employed by national and international governments, by businesses, and by universities. This talk will describe the formation of OSC and its 50 years of excellence.

9186-2, Session 1

Evolution of the graduate and undergraduate curricula in the College of Optical Sciences *(Invited Paper)*

Richard L. Shoemaker, College of Optical Sciences, The Univ. of Arizona (United States)

Upon its inception in 1968 as the Optical Sciences Center, only MS and PhD degrees were offered, with a core curriculum consisting of five courses plus a few electives. Since then the Center has become a college within the University of Arizona, offering an ABET accredited BS degree in Optical Engineering, MS and PhD degrees in Optical Sciences, and a number of graduate certificates. The development of the curricula for each of these degrees and certificates is discussed as well as how each curriculum attempts to meet the differing goals of the degrees offered.

9186-3, Session 1

Inexperienced as we were, it was ours to do! *(Invited Paper)*

Robert P. Breault, Breault Research Organization, Inc. (United States)

In 1969 the Science of Optics was being rekindled. Few of the professors were from the academic world. Just about everything we did was from scratch. We made our tools, we experimented to learn science that was never seen or known before; we performed principal roles on contracts; me on the Hubble. But there was always more to do such as starting companies for which we never had an hour of coaching. Then in a few years the Star Wars era hit and we did even more. It was an obligation in a way for us to do.

9186-4, Session 1

OSC in the 1970s: a springboard for a career in optical engineering

James E. Harvey, Photon Engineering LLC (United States)

Anecdotes and recollections from a graduate student at the Optical Sciences Center (OSC) in the late 1960s and early 1970s. The early faculty of the OCS fostered an exciting environment where even graduate students served significant roles on major government research contracts. Teamwork and collaboration between research groups was often required to meet the contract goals. This unique learning experience at the OSC almost 50 years ago served as a springboard for a satisfying and rewarding career in Optical Engineering.

9186-5, Session 2

Space optics contributions by the College of Optical Sciences *(Invited Paper)*

James B. Breckinridge, College of Optical Sciences, The Univ. of Arizona (United States); Peter H. Smith, The Univ. of Arizona (United States)

Over the past 50 years, the College of Optical Sciences (COS) and its predecessor The Optical Sciences Center made significant contributions to enable many scientific measurements from space with its cutting edge innovative technology programs in large mirrors, radiometry, polarization, camera designs, image processing, imaging spectrometers, IR detectors, IR cameras and many others. This unique capability contributed to the success of several NASA missions including HST, Mars Pathfinder, Pioneer 10/11, Pioneer Venus, and OSIRIS-REx. This paper reviews optics technologies developed at COS and their contribution to the success of the NASA mission.

9186-6, Session 2

Big optical systems for astronomy and solar energy *(Invited Paper)*

J. Roger P. Angel, The Univ. of Arizona (United States)

Over the past 50 years, Optical Sciences and Steward Observatory together have revolutionized the manufacture of large astronomical mirrors. Under the University of Arizona football stadium, the Mirror Lab now makes the largest of all, including the two 8.4 m diameter mirrors of the Large Binocular Telescope. Recently Roger Angel has picked up Aden Meinel's interest in solar energy. His group, which includes several Optical Sciences students, is developing novel ways to use concentrating optics with large glass mirrors to reduce the cost of solar electricity.

9186-7, Session 2

Large optics fabrication and testing at the College of Optical Sciences *(Invited Paper)*

James H. Burge, College of Optical Sciences, The Univ. of Arizona (United States)

The last decade has seen explosive growth in development and implementation of new technologies for manufacturing and measuring large optics at the College of Optical Sciences. The classic polishing techniques have given way to advanced computer controlled machines and highly engineered laps. New measuring methods have enabled accurate metrology of steeply aspheric surfaces, concave and convex,

symmetric and freeform. This paper reviews some recent major projects and the technical developments that have enabled their success.

9186-8, Session 3

Infrared optics at the College of Optical Sciences and in the world *(Invited Paper)*

William L. Wolfe, College of Optical Sciences, The Univ. of Arizona (United States)

No Abstract Available

9186-9, Session 3

A page from the drawer: how Roland Shack opened the door to the aberration theory of freeform optics *(Invited Paper)*

Kevin P. Thompson, Synopsys, Inc. (United States); Jannick P. Rolland, Univ. of Rochester (United States)

In 1976, astronomers working on Kitt Peak brought Prof. Shack a through-focus star field photograph from a newly commissioned telescope. Close inspection of the photograph clearly demonstrated that the telescope focal plane had no astigmatism at two separate and distinct points in the star field; a completely unexplained result. Simultaneously, Richard Buchroeder, put forth a concept related to a property of the aberration fields of a single surface that could be used for optical systems with tilted and decentered components. The photograph, combined with the insight put forward by Buchroeder, combined with work Prof. Shack had been doing independently to express the wave aberration function of H.H. Hopkins as a vector expression formed the basis for his new approach. However, the most spontaneous step was to come. Over the course of 1976/77 Prof. Shack took different approaches to the problem, as he often did. Along the way he introduced an archaic form of vector analysis, vector multiplication. Historically, vector multiplication was taught in standard courses on vector analysis and came to be referred to in some circles as Clifford, or, Geometric Algebra. However, in the 1930s a committee concluded it had inconsistencies and since then it is no longer taught. It is through this mathematical vehicle that Prof. Shack discovered the existence of multinodal aberration fields as a concept and binodal astigmatic fields in particular. 35 years later, these pivotal steps have led to a framework for discovering the aberration fields of imaging optical systems with freeform surfaces.

9186-10, Session 3

Optical Sciences Center at the U of A in the late seventies: times of consolidation

Marija Strojnik, Ctr. de Investigaciones en Óptica, A.C. (Mexico)

The Optical Sciences Center at the University of Arizona, to evolve into the Optical Sciences College, could be described by five periods roughly corresponding to the successive Center Directors. I will describe my experiences, impressions, and crystallized learnings as a graduate student in the late seventies. The Center was under the leadership of Professor Peter Franken. He was a wise and experienced manager of a highly successful team of scientists and engineers, while at the same time one of the founding fathers of the emergent field of non-linear optics. His challenges include aligning the Center with the University culture. I will compare and contrast my experience with education in Slovenia (Central Europe), where I first enrolled in Engineering physics; the Arizona State University, a regular Physics Department; and the University of California at Los Angeles where I perfected my management and people-issue training, having completed an MS degree in Engineering in the Engineering Executive Program. My Alma Mater, The University of Arizona, combined all those aspects of my academic preparation for professional career and paved the path of life-time enjoyment and love for optics.

9186-11, Session 3

Past, present, and future of optical design at the College of Optical Sciences *(Invited Paper)*

José Sasián, College of Optical Sciences, The Univ. of Arizona (United States)

This presentation reviews the accomplishments at the College of Optical Sciences in both teaching and contributing to optical design. Currently the College offers the world's most comprehensive curriculum in optical design and this presentation puts in perspective its history, accomplishments, and challenges.

9186-12, Session 4

First 25 years of quantum optics at the University of Arizona *(Invited Paper)*

Murray Sargent III, Microsoft Corp. (United States)

No abstract available

9186-13, Session 4

Quantum control and a novel atom-light quantum interface *(Invited Paper)*

Poul S. Jessen, College of Optical Sciences, The Univ. of Arizona (United States)

No abstract available

9186-14, Session 4

Progress of the quantum nano-optics of semiconductors group at Optical Sciences *(Invited Paper)*

Ricky Gibson Jr., Michael R. Gehl, Sander Zandbergen, Patrick Keiffer, Jasmine Sears, Galina Khitrova, College of Optical Sciences, The Univ. of Arizona (United States)

The history of semiconductor quantum optics group in the College of Optical Sciences will be discussed. The work from planar micro-cavities including VCSELs, photonic crystal cavities leading to the observation of strong-coupling between an L3 cavity and a quantum dot, and now metallic cavities coupled to quantum wells and quantum dots will be described.

9186-15, Session 4

Ultrafast light-matter coupling in condensed and gaseous nonlinear media *(Invited Paper)*

Miroslav Kolesik, College of Optical Sciences, The Univ. of Arizona (United States); Kolja Schuh, College of Optical Sciences, University of Arizona (United States); Stephan W. Koch, Philipps-Univ. Marburg (Germany); Jerome V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States)

Intense field, ultrafast interactions of light with gaseous and condensed media encompass a broad swath of extreme nonlinear interactions

ranging from the creation of light filaments to many-body interactions between anisotropic carriers (electrons, holes, ions, phonons). The ACMS research group at the College of Optical Sciences has been the leader worldwide in developing a theoretical understanding of this extreme physics associated with such ultrafast nonlinear events and in the experimental realization of new outcomes predicted by such theories.

After a brief historical review, recent research in the study of terawatt class femtosecond lasers propagating in air and condensed media will be first highlighted. Here critical self-focusing of the light field reflects the presence of a famous singularity (blow-up in finite time) in the governing Nonlinear Schrödinger equation – our talk will deal with moving into a regime where NLSE fails and more exact optical carrier resolved pulse propagators need to be developed and secondly, address the failure of well-established phenomenological nonlinear optical susceptibilities and their replacement by more fundamental quantum models. As second topic, we will discuss a combined theory/experimental effort that led to world record demonstrations of continuous wave and sub-picosecond mode-locked average power from an optically-pumped semiconductor disk laser. Interestingly, the many-body ultrafast correlations within and between electron-hole plasmas in an active semiconductor medium can be extended to treat the loss of anisotropy of the intense field generated photoionized electrons/ions as they evolve towards a classical plasma state in a dilute gas such as air.

9186-16, Session 5

Image science and image-quality research in the Optical Sciences Center *(Invited Paper)*

Harrison H. Barrett, College of Optical Sciences, The Univ. of Arizona (United States); Kyle J. Myers, U.S. Food and Drug Administration (United States)

This paper reviews the history of research into image quality, and the emergence of a science of imaging, with emphasis on the quarter century beginning in 1980. The work of various students in the Optical Sciences Center in the areas of psychophysical studies of human observers of images; mathematical model observers; image simulation and analysis, and the application of these methods to radiology and nuclear medicine is summarized. The implications of these advances to ongoing research and the current Image Science curriculum at the College of Optical Sciences are discussed.

9186-17, Session 5

History of digital radiology at the U of A *(Invited Paper)*

Hans N. Roehrig, Michael P. Capp M.D., The Univ. of Arizona (United States)

Little did anyone know that the first interaction of Bob Shannon with Paul Capp has led to over 40 years of combined research between a university basic science department and a clinical department starting the new medical school at the U of Az. Because of the relationship of the optical science center and department of radiology they were in a unique position to begin the first envelopment of digital radiology which led to the elimination of the old x-ray film; now replaced worldwide by electronic imaging. This has saved hundreds of millions of dollars in healthcare costs. The early steps of this development will be discussed. Thank you Bob Shannon.

9186-18, Session 5

Molecular imaging in the College of Optical Sciences: an overview of two decades of instrumentation development *(Invited Paper)*

Lars R. Furenlid, Harrison H. Barrett, College of Optical Sciences, The Univ. of Arizona (United States); H. Bradford Barber, Eric W. Clarkson, The Univ. of Arizona (United States); Matthew A. Kupinski, College of Optical Sciences, The Univ. of Arizona (United States); Zhonglin Liu, Gail D. Stevenson, James M. Woolfenden, The Univ. of Arizona (United States)

During the past two decades, we have explored a variety of approaches to gamma-ray detection, including scintillation cameras, solid-state detectors, and hybrids such as the intensified Quantum Imaging Device (iQID) configuration where a scintillator is followed by optical gain and a fast CCD or CMOS camera. Wherever possible, we use maximum-likelihood (ML) methods to estimate the attributes of each gamma interaction event, including its 3D location, the energy deposited, and the event time. We store all of these estimates, without binning or windowing, in a large multidimensional list, with information content far exceeding that of conventional digital data. We call the acquisition of image data as a list of photons and their attributes “super-list-mode.”

Building on the “super-list-mode” concept, we have developed a large number of preclinical molecular-imaging systems that perform emission tomography, SPECT and PET, sometimes in conjunction with CT. We have made use of a variety of collimation schemes, including single and multiple pinholes, parallel-hole collimators, synthetic apertures, and anamorphic crossed slits. Our systems are characterized by their unique dynamic capabilities (no motion of the subject, aperture or detector); their large number of intrinsic resolution elements; their unprecedented reconstructed spatial resolution, in some cases reaching 100 μm; their extraordinary energy resolution (<1% FWHM with a CdTe detector from our collaborators at JAXA); and their highly accurate calibrations. In this paper, we will trace the thread of conceptual and technological advances we have made in developing these systems.

9186-19, Session 5

An information-theoretic approach to compressive imaging *(Invited Paper)*

Amit Ashok, College of Optical Sciences, The Univ. of Arizona (United States)

Compressive imaging exploits sparsity/compressibility of natural scenes to reduce the detector count/read-out bandwidth in a focal plane array by effectively implementing compression during the acquisition process. Random measurement basis have been the traditional choice for implementing compressive imaging systems based on their universal signal agnostic design. However, such projections ignore the structured sparsity inherent in most natural scenes and signals. We have developed a rigorous information-theoretic approach for non-random compressive measurement design that incorporates signal and task priors along with hardware constraints to address this shortcoming. Information-optimal compressive measurement designs achieve significant performance improvements relative to random design. We will illustrate these performance gains via simulation studies and experimental validation.

9186-20, Session 6

From the outside looking in: developing snapshot imaging spectro-polarimeters *(Invited Paper)*

Eustace L. Dereniak, College of Optical Sciences, The Univ. of Arizona (United States)

No Abstract Available

9186-21, Session 6

Multilayer soft x-ray optics *(Invited Paper)*

Charles M. Falco, College of Optical Sciences, The Univ. of Arizona (United States)

This paper describes work on multilayer soft x-ray optics conducted in the College of Optical Sciences and funded by the AFOSR and JSOP.

9186-22, Session 6

Noise, error, and bandwidth in polarimeters *(Invited Paper)*

J. Scott Tyo, College of Optical Sciences, The Univ. of Arizona (United States)

Polarimeters are information systems that infer the distribution of polarization information in space, time, wavelength, or in multiple domains simultaneously. Various types of polarimeters achieve this using different measurements strategies, all of which affect noise, error, and bandwidth of the resulting system in different ways. This talk will review the work over the past 15 years that has led to a greater understanding of the performance tradeoffs in imaging polarimeters.

9186-23, Session 6

Past and future of wearable augmented reality displays and their applications *(Invited Paper)*

Hong Hua, College of Optical Sciences, The Univ. of Arizona (United States)

A wearable augmented reality (AR) display enables the ability to overlay computer-generated imagery on a person's real-world view and it has long been portrayed as a transformative technology to redefine the way we perceive and interact with digital information. In this talk, I will provide an overview on past technological advancements and application examples, demonstrate examples of AR displays developed in my group based on emerging freeform optics, and their applications, and discuss key technical challenges and opportunities for future developments.

9186-24, Session 7

Developments in the photonics program at OSC *(Invited Paper)*

Nasser N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States)

The photonics program at the College of Optical Sciences started nearly 30 years ago. Initially in 1984, the program was focused on development of femtosecond laser sources and their use in investigating semiconductor carrier dynamics. The program grew into polymer and organic optics in late 1989 and was strengthened by the winning of the Center for Advanced Multifunctional Nonlinear Optical Polymers and Molecular Assemblies (CAMP) Multidisciplinary University Research Initiative (MURI) from ONR in 1995 that was focused on multifunctional polymers, including photorefractive polymers, organic light emitting diodes and 3D direct laser writing. Also in 1995, the areas of glass waveguide and fiber optic materials and devices were added to the program. In 2008 we added the optical communication and future internet research through winning the Center for Integrated Access Networks (CIAN) NSF ERC. Expertise in thin films, optical storage and the fundamental aspects of light are elements of the overall research program. Holographic 3D display, autofocus lenses, bioimaging and devices for vision have also been ongoing research areas.

9186-25, Session 7

A three-decade-long journey at the College of Optical Sciences *(Invited Paper)*

Dror Sarid, College of Optical Sciences, The Univ. of Arizona (United States)

In 1980, Peter Franken, the second director of the Optical Sciences Center, recruited an international quartet from the US (Hyatt Gibbs), Canada (George Stegeman), England (Angus Macleod) and Israel (me), all as full professors. Sharp as a scalpel, bright as a sun, super-organized and wildly outspoken, Peter shaped the Center as a clockwork operation, nailing down every aspect of its administration, business model and academic vision. I found myself from day one in a highly competitive environment with extreme peer pressure to make good science and generate (a lot of) funds. This paper describes the academic journey through my three decades at the College until my retirement in 2010, by highlighting selected areas of my group's research:

(a) Long-range surface plasma waves on very thin metal films, Phys. Rev. Letts. (1981)

(b) Holographic display of scanning tunneling microscopy images, Opt. News (1988)

(c) Scanning tunneling microscopy and spectroscopy of individual C60 on Si(100)-(2x1) surfaces, Surf. Sci. Lett. (1988)

(d) Study of carbon nanotubes by STM, AFM, and high-resolution transmission electron microscopy, Surf. Sci. Lett. (1993)

(e) Compact scanning force microscope using a laser diode, Opt. Lett. (1988)

(f) High resolution Fowler-Nordheim field emission maps of thin silicone oxide layers, Appl. Phys. Lett. (1996)

(g) Individually injected current pulses with a conducting-tip, tapping-mode atomic force microscope, Science (2002)

(h) Exploring scanning probe microscopy with Mathematica, Wiley (2007)

These were made possible by strong collaborations within the Center, across campus and outside scientists.

9186-26, Session 7

Nanophotonic materials and devices: driving the big data engine *(Invited Paper)*

Robert A. Norwood, College of Optical Sciences, The Univ. of Arizona (United States)

Photonics has been critical in the growth of the Internet that now carries a tens of exabytes per month over optical fiber. The future growth of information technology, including the transmission and processing of vast amounts of data, will require a new class of photonic devices that readily integrate directly with semiconductor circuits and processors. Nanophotonics will play a key role in this development, providing both designer optical materials and radically smaller and lower power consumption devices. We will present our developments in engineered nanophotonic polymer materials and electro-optic polymer/silicon nanowire devices in the context of this burgeoning field. We have developed polymer nanoparticle composite materials that are the first magneto-optic materials to be processable and completely compatible with silicon photonics, and which hold promise for both integrated optical isolators and ultrasensitive magnetic field probes, by virtue of their large Verdet constants, equivalent to the commercially available YIG crystal at 1550nm wavelength. The combination of state-of-the-art electro-optic polymers, with EO coefficients greater than 200pm/V and silicon nanophotonic waveguides will be discussed as a potential platform for ultrahigh speed, low voltage, compact photonic modulators and switches.

9186-27, Session 7

Mechanical effects of light on material media: radiation pressure and the linear and angular momenta of photons *(Invited Paper)*

Masud Mansuripur, College of Optical Sciences, The Univ. of Arizona (United States)

Electromagnetic waves carry energy as well as linear and angular momenta. Interactions between light and material media typically involve the exchange of all three entities. In all such interactions energy and momentum (both linear and angular) are conserved. Johannes Kepler seems to have been the first person to notice that the pressure of sunlight is responsible for the tails of the comets pointing away from the Sun. Modern applications of radiation forces include solar sails, optical tweezers for optical trapping and micro-manipulation, and optically-driven micro-motors and actuators. We describe certain fundamental aspects underlying the mechanical effects of light, and examine several interesting phenomena involving the linear and angular momenta of photons.

9186-28, Session 8

Optical metrology at the Optical Sciences Center: an historical review *(Invited Paper)*

Katherine Creath, College of Optical Sciences, The Univ. of Arizona (United States) and Optineering (United States); Robert E. Parks, Optical Perspectives Group, LLC (United States) and College of Optical Sciences, The Univ. of Arizona (United States)

The Optical Sciences Center (OSC) begun as a graduate-level applied optics teaching institution to support the US space effort. The making of optics representative of those used in other space programs was deemed essential. This led to the need for optical metrology: at first Hartmann tests, but almost immediately to interferometric tests using the newly invented HeNe laser. Not only were new types of interferometers needed, but the whole infrastructure that went with testing, fringe location methods, aberration removal software and contour map generation to aid the opticians during polishing needed to be developed.

Over the last half century more rapid and precise methods of interferogram data reduction, surface roughness measurement, and methods of instrument calibration to separate errors from those in the optic have been pioneered at OSC. Other areas of research included null lens design and the writing of lens design software that led into the design of computer generated holograms for asphere testing. More recently work has been done on the reduction of speckle noise in interferograms, methods to test large convex aspheres, and a return to slope measuring tests to increase the dynamic range of the types of aspheric surfaces amenable to optical testing including free-form surfaces.

This paper documents the history of the development of optical testing projects at OSC and highlights the contributions some of the individuals associated with new methods of testing and the infrastructure needed to support the testing. We conclude with comments about the future direction of optical metrology.

9186-29, Session 8

History of the Shack Hartmann wavefront sensor and its impact in ophthalmic optics *(Invited Paper)*

Jim Schwiegerling, College of Optical Sciences, The Univ. of Arizona (United States)

The Shack Hartmann wavefront sensor is a technology that was developed at the Optical Sciences Center at the University of Arizona in the late 1960s. It is a robust technique for measuring wavefront error that was originally developed for large telescopes to measure errors induced by atmospheric turbulence. The Shack Hartmann sensor has evolved to become a relatively common non-interferometric metrology tool in a variety of fields. Its broadest impact has been in the area of ophthalmic optics where it is used to measure ocular aberrations. The data the Shack Hartmann sensor provides enables custom LASIK treatments, often enhancing visual acuity beyond normal levels. In addition, the Shack Hartmann data coupled with adaptive optics systems enables unprecedented views of the retina. This talk traces the evolution of the technology from the early use of the Hartmann screen, to the incorporation of lenslet arrays and finally to one of its modern applications, measuring the human eye.

9186-30, Session 8

Half a century of light scatter metrology and counting *(Invited Paper)*

John C. Stover, The Scatter Works Inc. (United States)

Back in the early days Bill Wolf once said something like: “The guy with the lowest scatter measurement is closest to the right answer.” He was right then – but not anymore. Everything has changed. Today measurements are limited by Rayleigh scatter from the air – not the instrument. We have both written and physical standards and everybody spells BRDF the same way. In the time it takes to give this talk, over 100,000 silicon wafers will be inspected around the world using a few thousand scatterometers – average price about one million dollars each. The way the world illuminates everything from homes to football fields is changing with the advent of high brightness LED’s and these lighting systems are designed using a combination of scatter metrology and analysis techniques – many of which were started at The Optical Sciences Center. This paper reviews highlights in half a century of progress in scatter metrology.

9186-31, Session 8

Interferometry and ophthalmics at the College of Optical Sciences *(Invited Paper)*

John E. Greivenkamp, College of Optical Sciences, The Univ. of Arizona (United States)

A long-term research program has been in place at the College of Optical Sciences to apply interferometry to ophthalmic applications. These unique systems have been developed in response to industrial need. The first system is a transmission Mach-Zehnder interferometer used to measure the transmitted wavefront of a contact lens while it is submersed in saline. This interferometer allows the refractive power distribution of the lens to be measured, and the system can serve as part of a quality control tool for manufacturing. A second system makes use of a low-coherence interferometer to measure the index of refraction of contact lens material. This task is complicated by the fact that the material is only available in very thin, flexible samples, and because the sample must remain hydrated in saline during the measurement. Two addition interferometers examine tear film dynamics on the surface of a contact lens (in vitro) and on the surface of the cornea (in vivo). Both systems are instantaneous phase-shifting Twyman-Green interferometers. The evolution and changes to the fluid surface is measured at video rates with sub-wavelength precision. This paper tells the story of this research program.

9187-17, Session 1

Atmospheric optics in art *(Invited Paper)*

Stanley D. Gedzelman, The City College of New York (United States)

No Abstract Available

9187-2, Session 2

Natural case of multifunctional nanostructured surfaces: the wing of the grey cicada (Cicada orni)

Louis Dellieu, Michaël Sarrazin, Priscilla Simonis, Olivier Deparis, Univ. of Namur (Belgium)

The wing of the grey cicada Cicada orni exhibits interesting properties for photonics and self-cleaning. Transmission reaches nearly 100% and scatterometry measurements, performed at different incidence angles, show no diffusive character whatever the polarization of the incident beam is. Wetting experiments reveal hydrophobic character of the wing, with an apparent contact angle of 146°, close to the superhydrophobicity threshold (150°). For a better understanding of the wing hydrophobicity, contact angles were measured using various liquids with different surface tensions. The results show a transition from a hydrophobic regime to a hydrophilic regime, according to the liquids surface tension.

In order to understand the origin of these observed surface properties, scanning electron microscopy imaging of the wing was realized revealing the presence of intricate nanostructures covering the wing on both sides. Numerical simulations based on a detailed photonic model of the wing were performed to assess the optical properties of the grey cicada. Analytical model was used to describe the hydrophobicity of the wing. Two entangled levels of functionality were identified in the nanostructures which cover the wings of the grey cicada: an upper level responsible for the hydrophobic character and a lower level responsible for anti-reflective behavior.

9187-3, Session 2

Polarimetry of light from iridescent shells

Enrique J. Galvez, Rebecca Metzler, Carrie Burgess, Brian Regan, Colgate Univ. (United States)

We investigate the light transmitted or reflected from nacre (mother-of-pearl) from several types of iridescent shells, including pearl oysters and abalone. These surfaces have a rich structure, composed of aragonite crystals arranged as tablets or “bricks,” 5 micrometer long and 400-500 nm thick, surrounded by 30–nm thick organic “mortar.” The light reflected from these shell surfaces, or transmitted through thin polished layers, is rich in its polarization content, exhibiting a space dependent variation in the state of polarization with a high density of polarization singularities. We use the polarization information to infer the structure of the biominerals and the role of the organic layer in determining the orientation of the crystals. In the experiments we send the light from a laser with a uniform state of polarization onto the shell, and analyze the light that is transmitted or reflected, depending on the type of experiment, imaging it after its passage through polarization filters. We use the images from distinct filters to obtain the Stokes parameters, and hence the state of polarization, of each image point. We do this for distinct chemical treatments of the shell sample. Preliminary data shows that the organic layer may be responsible for disrupting an otherwise orderly multi-crystalline arrangement of aragonite tablets. These studies are complemented by x-ray analysis of the aragonite tablets.

9187-4, Session 3

Light extraction enhancement for light-emitting diodes: a firefly-inspired structure refined by the genetic algorithm

Annick Bay, Univ. of Namur (Belgium) and Univ. of California, San Diego (United States); Alexandre Mayer, Univ. of Namur (Belgium)

The efficiency of light-emitting diodes (LED) has increased significantly over the past few years, but the overall efficiency is still limited by total internal reflection due to high refractive index contrast between the incident and emergent medium. The bioluminescent organ of fireflies gave incentive for light extraction enhancement studies. A specific “factory-roof” shaped structure was shown, by means of light propagation simulations and measurements, to enhance light extraction significantly. In order to achieve a similar effect for light-emitting diodes, the structure needs to be adapted to the specific set-up of LEDs. In this context simulations were carried out to determine the best geometric parameters [1].

In the present work, the search for a high-extraction efficiency geometry has been conducted using a genetic algorithm [2,3]. The idealized structure considered previously was generalized to a broader variety of shapes. The genetic algorithm makes it possible to search simultaneously over a wider range of parameters and is significantly less time-consuming than the previous approach.

The results of the genetic algorithm show that (1) the calculations can be performed in a smaller amount of time and (2) the light extraction can be enhanced even more significantly by choosing precisely the geometrical parameters of the generalized structure.

The combination of the genetic algorithm and the light propagation calculation constitutes a strong simulation tool, that provides us with an adapted design for extraction-enhancing structures on light-emitting diodes inspired by Nature.

[1] A. Bay et al. , Opt. Express, 21, A179-A189 (2013)

[2] R. Judson, in “Reviews in Computational Chemistry”, vol. 10, chap. 1, pp 1-73

[3] D. Nicolay, Master thesis, UNamur (2012)

9187-5, Session 3

Genetic algorithms used for the optimization of light-emitting diodes and solar thermal collectors

Alexandre Mayer, Annick Bay, Lucie Gaouyat, Delphine Nicolay, Timoteo Carletti, Olivier Deparis, Univ. of Namur (Belgium)

Genetic algorithms mimic natural selection in order to determine the optimal parameters of complex problems in physics. The idea consists in working with a population of individuals, each of them representing a given set of parameters and therefore a given value of the function we seek at optimizing. The initial population consists of individuals with random parameters. We then select the best individuals for the next generation. We also breed them in order to determine new individuals. Mutations are finally introduced in order to maintain diversity. When applied from generation to generation, this strategy makes it possible to get closer and closer to the global optimum of a problem.

We applied the genetic algorithm to the optimization of light-emitting diodes (LED) [1]. The surface of a LED can be covered by periodic structures whose geometrical and material parameters must be adjusted in order to optimize the extraction of light. We also used the genetic algorithm in order to optimize the geometrical parameters of a waffle-shaped aluminium substrate used to enhance the efficiency of solar collectors [2]. We must in this case maximize solar absorption while minimizing the thermal emissivity in the infrared. This presentation

will serve as introduction to multi-objective genetic algorithms. It will be illustrated by the optimization of light-emitting diodes and solar collectors.

[1] A. Bay, N. André, M. Sarrazin, A. Belarouci, V. Aimez, L.A. Francis and J.-P. Vigneron, Optics Express 21, A179-A189 (2013)

[2] L. Gaouyat, F. Mirabella and O. Deparis, Applied Surface Science 271, 113-17 (2013)

9187-6, Session 3

Efficient spectral light focusing in microstructured marine diatom

Arne Røyset, SINTEF (Norway); Julien Romann, Norwegian Univ. of Science and Technology (Norway); Jean Christophe Valmalette, Univ. du Sud Toulon-Var (France)

We report on new insight in the light focusing properties of single diatom frustule valves with radial symmetry. Experimental and numerical results are presented for the Coscinodiscus wailesii and Coscinodiscus centralis species, which both consist of two layers of hexagonally oriented hole patterns separated by a hexagonal wall structure. Confocal hyperspectral transmission mapping are used to obtain detailed spectral maps of the light focusing with µm resolution. Numerical diffraction calculations are carried out to investigate the relation between structural parameters and the spectral and spatial light focusing properties. A strong wavelength dependence in the focused light patterns are observed experimentally, and it is found that this can be explained and predicted by the diffraction properties of the frustule. The experimental results demonstrates markedly different focusing behavior of the two species, while the numerical results reveal that this can be explained by the much larger height of the hexagonal wall structure in the centralis diatom. Our numerical results also reveal the importance of the radial symmetry of the frustule for efficient light focusing. Optical properties are also compared for frustules in water and air. The implications for light harvesting in living diatom and for biomimetic diatom applications are discussed.

9187-7, Session 4

Insights of finite difference models of the wave equation and Maxwell's equations into the geometry of space-time

James B. Cole, Univ. of Tsukuba (Japan)

The finite difference time domain (FDTD) algorithm is a popular tool for photonics design and simulations, but it also can yield deep insights into the fundamental nature of light and - more speculatively - into the discretization and connectivity and geometry of space-time.

The CFL stability limit in FDTD can be interpreted as a limit on the speed of light. It depends not only on the dimensionality of space-time, but also on its connectivity. Thus the speed of light not only tells us something about the dimensionality of space-time but also about its connectivity. The computational molecule in conventional 2-D FDTD is (x +/- h,y)-(x,y+/-h)-(x,y), where h=delta_x= delta_y. It yields the CFL stability limit c delta_t / h less than or equal 1 / square_root(2). Including diagonal nodes (x+/-h, y+/h) in the computational molecule changes the connectivity of the space and changes the CFL limit. The FDTD model also predicts precursor signals (which physically exist). The Green's function of the FDTD model, which differs from that of the wave equation, may tell us something about underlying periodicities in space-time. It may be possible to experimentally observe effects of space-time discretization and connectivity in optics experiments.

9187-16, Session 4

Simulating the colors of thermal features at Yellowstone National Park

Joseph A. Shaw, Paul W. Nugent, Montana State Univ. (United States); Michael Vollmer, Fachhochschule Brandenburg (Germany)

Thermal pools in Yellowstone National Park are famous for their rich and varied colors. Colors of shallow pools tend to be driven primarily by pigmented bacteria within the microbial mat, while colors of deeper pools are dominated by absorption and scattering of sunlight in the water. We combined measured spectra with a simple computer model of reflection, absorption, and scattering to simulate the colors of several well-known thermal features. The simulation results are compared qualitatively to visible photographs.

9187-9, Session 5

Counterintuitive color changes in Hoplia coerulea photonic nanostructure upon liquid impregnation

Sébastien R. Mouchet, Univ. of Namur (Belgium); Bao-Lian Su, Univ. of Namur (Belgium) and Wuhan Univ. of Technology (China) and Univ. of Cambridge (United Kingdom); Olivier Deparis, Univ. of Namur (Belgium)

Physical colors are known to be produced by various natural photonic structures in living organisms such as insects. These porous structures are ordered at the wavelength scale and made of chitin. Their impregnation with water, e.g. in wetting experiments, may give rise to color changes. On the other hand, color change of Morpho wings in contact with ethanol is also well-known and is used to discriminate pigmentary colors and physical colors.

In this work, we performed impregnation experiments of Hoplia coerulea scales with two different liquids (water and ethanol) which have different liquid-solid surface tensions with bulk chitin. The observed color changes were found to be counterintuitive. Indeed, they appeared to be faster for water (a few seconds) than for ethanol (about half a minute) while chitin should have more affinity with ethanol than with water. The dynamics of color changes were quantified by real-time reflectance spectral measurements and microscope movies.

The origin of these intriguing color changes has therefore to be tracked in microscopic phenomena. Synergistic effects of physical and chemical properties of the studied structure were investigated by contact angle measurements, porosimetry and X-Ray photoelectron spectrometry (XPS). This phenomenon observed in a natural porous structure could be very interesting for vapor sensing applications and smart glass windows.

9187-10, Session 5

Structural-based blue appearance in tarantulas

Bor-Kai Hsiung, Chad M. Eliason, Todd A. Blackledge, Matthew D. Shawkey, The Univ. of Akron (United States)

Photonic crystals are periodic nanostructures that interact with electromagnetic waves, and can be found in nature not only in gems but also in living organisms, where they create so-called "structural colors". These colors are usually iridescent and account for almost all of the blue hues found in animals. However, most research on structural colors has focused on bird plumage or butterfly wings, and collectively suggest that coherent light scattering by ordered photonic crystals is the main mechanism that results in iridescent structural colors. Here, we describe the proximate mechanisms responsible for blue color in

three tarantula species, Haplopelma, Lampropelma and Euathlus. The reflectance spectra measured from single hairs from the tarantulas show that the blue hairs have peaks around 400~450 nm, while non-colored hairs do not. SEM images demonstrate that blue hairs have smoother surface morphologies while non-blue hairs are spiky. TEM images of the hairs' cross sections present conspicuous multilayer nanostructure in the blue hairs of Lampropelma. Fourier transform analysis of these images show different degrees of periodicity, while images from non-blue hairs are amorphous and lack periodicity. A model based on the observed multilayer structure predicts a reflectance spectrum that closely matches our measurements. This study will help us understand if chitin-based structures in spiders evolve convergently with keratin/melanin-based structures in vertebrates, if they may serve some functions other than signaling and could contribute to creating biomimetic photonic crystal fabrication processes or products.

9187-11, Session 5

Eye movement strategies in visual search: effect of peripheral information

Tatjana Pladere, Ieva Timrote, Gunta Krumina, Univ. of Latvia (Latvia)

In the natural world, a visual stimulus is generally surrounded by a number of other irrelevant stimuli. During the visual search, we make series of saccadic eye movements interleaved with periods of gaze fixation. Central vision serves the function of differentiating the target from other stimuli, so called distracters. In turn, peripheral vision is essential in the process of programming next eye movement. Thus, the visual search is used to investigate the interaction between different processes, such as, eye movement coding, central and peripheral vision. The main purpose of our study is to determine the influence of certain peripheral information on the efficiency of visual search and changes in eye movement strategies. In the developed visual search task, an individual has to find and count specific letters. What is more, different kind of peripheral information is provided – distracter letters differ with color and/or thickness. The eye gaze position was registered using camera with near-infrared illumination. The results reveal that eye movement strategy changes significantly for each individual according to the provided peripheral information. If distracters differ with color, the amplitude of saccadic eye movements increases, but the fixation duration becomes longer. Overall, the optimization of scanning strategy improves the time needed to accomplish the task. But it does not have strong influence on the accuracy of the visual search.
The work was partly supported by European Social Fund project No. 2013/0021/1DP/1.1.1.2/13/APIA/VIAA/001.

9187-12, Session 6

A graphitic structure responsible for the blue coloration?

Priscilla Simonis, Univ. of Namur (Belgium); Abigael Ingram, Natural History Museum (United Kingdom)

Many different ways are found by nature to display a given color. Among them, the well-known one-dimensional Bragg mirror can produce an iridescent bright blue. This presentation will focus on a new structure found in butterfly wing scales which looks like a giant graphitic layered structure. This structure is studied experimentally as well as theoretically and is found to be responsible for the blue coloration. The quasi one-dimensional graphitic model is compared to other possible structure's models. This kind of macroscopic graphitic structure could have many other applications. These applications, like mechanical properties, could be as strong as the graphene ones.

9187-13, Session 6

Fabrication of hierarchical optical active nanostructures inspired by the blue Morpho butterfly utilizing laser interference lithography

Radwanul Hasan Siddique, Abrar Faisal, Ruben Hünig, Karlsruher Institut für Technologie (Germany); Irene Wacker, Univ. Heidelberg (Germany); Uli Lemmer, Hendrik Hoelscher, Karlsruher Institut für Technologie (Germany)

Morpho butterflies are well-known for their famous non-iridescence blue originating from the complex hierarchical Christmas tree like nanostructure in the scales of their wings (see, e.g., Siddique et al., Opt. Exp. 21, 14351 (2013)). Although Morpho nanostructures are potential candidates for applications ranging from sensors to displays and textiles; their exact replication - especially on large scales - still remains a challenge due to the complexity and small dimensions of the Christmas tree like structure. Here, we introduce a technique to fabricate this complex morphology utilizing dual beam interference lithography on a glass substrate. A reflective optical coating is used to create a second interference pattern in vertical direction. These 85 nm thin patterns act as lamellas and the 1D grating structures as ridges. The photoresist is chosen accordingly to create the 'Christmas tree' shape. The artificial Morpho replica shows brilliant blue iridescence up to an incident angle of 40°. It outperforms the existing multilayer replica in terms of the optical properties because of the low refractive index difference of air and the polymer. Moreover, the biomimetic surface is strongly water repellent and features a self-cleaning effect as observed on the original Morpho butterfly wing.

9187-14, Session 6

Radiative thermal insulation in animal furs and feathers

Priscilla Simonis, Univ. of Namur (Belgium)

Radiation's contribution to thermal insulation is studied. It's mechanism as well as it's implication on fur and feather's insulation is presented. The mechanism by which a stack of absorbers limits radiative heat transfer is examined in detail both for black-body shields and grey-body shields. It shows that radiation energy transfer rates should be much faster than conduction rates. It demonstrates that, for opaque screens, increased reflectivity will dramatically reduce the rate of heat transfer, improving thermal insulation. This simple model contributes to the understanding of how animal furs operate. The cases of polar bear and white peacock will be presented and their relative thermal insulation power discussed.

9187-15, Session 7

Observing auroras and noctilucent clouds from an airplane window

Joseph A. Shaw, Montana State Univ. (United States)

A previous paper used photographs taken from commercial airplanes to illustrate the variety of optical displays that can be observed by an informed and alert observer from an airplane window. This paper expands this discussion to observing the high-latitude optical phenomena of auroras and noctilucent clouds. Observing tips are provided to enhance the probability of seeing certain phenomenon, based on the time of day, location, and direction of travel of the airplane. Generally, a seat on the northward-viewing side of the plane is required for viewing these phenomena in the northern hemisphere (and reverse in the southern hemisphere). Tips are given for how to not only successfully observe, but also to photograph these exotic optical phenomena from the air.

9188-23, Session PMon

An overview of the European patent system with particular emphasis on IP issues for imaging devices and OLEDS

Ana Cabrita, Mauro Boero, Marylene Faou, European Patent Office (Netherlands)

In this article we give a comprehensive review of the European Patent System with focus on the procedure, its typical duration, the requirements that must be met at the various stages in order to obtain an European Patent and its related costs. All the options available to the applicant are discussed in detail, potential pitfalls are highlighted, and the differences between the European and US and other patent systems are analysed.

Furthermore, an in-depth and very informative analysis of applications and granted patents in the field of imaging devices. solar cells, and OLED devices is presented including a study of their evolution during the last 10 years together with an analysis of the countries and companies that are most active in these fields.

9188-24, Session PMon

Optics outreach activities with elementary school kids from public education in Mexico

Perla M. Viera-González, Guillermo E. Sánchez-Guerrero, Juan C. Ruiz-Mendoza, Gustavo A. Cárdenas-Ortíz, Daniel E. Ceballos-Herrera, Romeo J. Selvas-Aguillar, Univ. Autónoma de Nuevo León (Mexico)

The Science enrollment in Mexico is a great challenge considering that there is not an established methodology for teaching using active process like hands-on activities.

This work shows the results obtained from the Optics Outreach Project, O4k, supported by SPIE trough UANL SPIE Student Chapter. Using the facilities of the Universidad Autonoma de Nuevo Leon in Mexico, undergraduate and postgraduate students designed optics representative activities using easy-access materials that allow the interaction of children with the light behavior and the process of image formation over the exploration, observation and experimentation, taking as premise that the best way to learn science is the interaction and practice with it. In the first stage of this project, several activities were realized through the 2012-2013 events with 1600 kids with ages from 10 to 12; the results of these activities were analyzed using surveys about the opinions and experiences of the kids, one of the principal conclusions is that in most of the cases the children changed their opinions about sciences, founding that the optics could be interest, amazing and fun.

9188-25, Session PMon

Summer school in Kabardina-Balkaria by BMSTU SPIE student chapter

Nikita V. Chernomyrdin, Arsenii A. Gavdush, Bauman Moscow State Technical Univ. (Russian Federation)

Last summer BMSTU SPIE Student Chapter have decided to visit Kabardino-Balkaria Republic of Caucasus (Russia) and spent there a week with children in a camp. It was called “Summer school”. We decided to organize it in order to engage talented and curious children in Optics and to show them how science could be funny. Education and entertainment program included such activities as lectures, optical demonstrations, laser games, hiking in the forest, and others. As a result children had a good time outdoors, learned interesting facts and about optics and lasers, and of course found new friends who are keen to know more too. Four Chapter members and about 70 children of age 10-16 took part in this event.

9188-26, Session PMon

Outcome-based learning optics in schools

M. Esakki Muthu Raju, Badrinath Vadakkapattu Canthadai, Vidya Jyothi Institute of Technology (India)

This paper describes the work of SPIE student chapter members to create interest in students on optics by teaching the students of upper primary schools in and around college premises the fundamental concepts of light such as reflection, refraction, diffraction, etc. This paper discusses on how students are interested in experimental learning rather than the traditional way of learning. In order to achieve this type of learning, students were divided into groups and had organized camps in rural schools. As a part of the project, we have conducted a workshop and assessed student learning outcomes on the concepts of light. Students were also asked to create models on their own related to optics. In order to motivate them these models will be exhibited. The goals of our assessments were to improve our understanding of how students learn key optics - related principles and provide evidence of the learning outcomes on the subject. Our research established that students in every classroom learned optics concepts, uncovered ideas about optics, and identified ways to support and supplement the curriculum for use in classrooms.

9188-27, Session PMon

Solar-powered model vehicle competitions

Nazmi Yilmaz, Ali Serpenguzel, Koç Univ. (Turkey)

Koç University SPIE student chapter, has been organizing solar powered model vehicle races and outreaching many K-12 students. The first solar powered model car race (2006), the first solar powered model boat race (2007), the first solar powered model blimp race (2008), the first solar powered “all solar” model boat race in (2009), the first solar powered model submarine race (2010), the first solar powered model underwater rower race in (2011), the first solar powered amphibious vehicle race in (2012) and the first solar powered model glider race (2013) has been successfully organized. A wide majority of these races are worldwide firsts to the best of our knowledge.

9188-28, Session PMon

Easing wave optics understanding through technology

Amit Garg, Priyanka Kachru, Subhajit K. Dutta, Ananya Paul, Acharya Narendra Dev College (India)

As part of the course curriculum of Physics of class XII, students do a comprehensive theoretical study about the wave nature of light specially related to interference, diffraction and polarisation. But, these studies are not backed up by any experiments. This makes the understanding of these complex topics very difficult. The purpose of the present outreach activity is to make students do many hands-on experiments on the above topics. The experiments have been designed keeping in mind the various theoretical concepts taught to the students. The studies are helpful in making the students understand fringe formation, intensity variation across the fringes formed helping them compare interference and diffraction fringes, dependence of fringe separation on various parameters, linear polarization, Malus' law and Brewster's law. The tools used to perform the experiments include He-Ne laser(s), light sensor, data acquisition device, Digital Storage Oscilloscope, CCD, various optical components like Fresnel bi-prism, set of polarisers and analysers,

glass plate and hardware components like single slit and double slit. The class XII students are divided into batches and each batch is handled by a team of three University of Delhi at ANDC SPIE student chapter members. The gains of the activity are measured through pre and post tests.

9188-1, Session 1

ETOP: the reference conference in education and training in optics and photonics. an overview of the 12th edition *(Invited Paper)*

Manuel F. Costa, Univ. do Minho (Portugal); Mourad Zghal, Univ. of Carthage (Tunisia); Zohra Ben Lakhdar, Univ. El Manaur (Tunisia); Vasudevan Lakshminarayanan, Univ. of Waterloo (Canada)

The teaching and learning of optics and photonics, critical fields at the core of today's scientific and technological infrastructure, must continually be upgraded and renewed in order to meet the growing demands of research, science and industry for the sake of the sustainable development of our world and humankind.

The International Conference on Education and Training in Optics, known as ETOP, promoted by SPIE, OSA, IEEE, and ICO, is the principal conference that brings together the international community of optics and photonics educators, leading optics and photonics scientists, academia, and industry, from all around the world to share experiences and knowledge, to discuss, demonstrate and learn about new developments and approaches to teaching in these fields.

Through presentations, panel discussions, workshops and exhibits, it is the intent of this conference to inform professors, students, teachers and professional trainers on how to promote the learning of optics and photonics for the future.

Since 1988, SPIE, the International Society for Optics and Photonics, and OSA, The Optical Society, have sponsored the ETOP conference. The first meeting, initiated by SPIE's Academic Advisory Committee, focused on undergraduate and master's level programs in optics and related fields, the supply and demand for graduates, and academia-industry interaction. The first ETOP was held in conjunction with SPIE's annual meeting in San Diego. It brought together scientists, technicians and educators to discuss educational programs and the opportunities and challenges for graduates. The second conference was held in 1991 in St Petersburg, Russia, for which the ICO joined the founding organizations as a co-sponsor. From there, ETOP became a biennial meeting that has been held in Pecs, Hungary (1993); San Diego, California, USA (1995); Delft, the Netherlands (1997); Cancun, Mexico (1999); Singapore (2001); Tucson, Arizona, USA (2003); Marseille, France (2005); Ottawa, Ontario, Canada (2007); and St Asaph, Wales (2009). The 2011 conference was scheduled to be held in Tunisia but was cancelled by the ETOP Long Range Advisory Committee because of the civil unrest in the region.

ETOP'2013 was then held 23–26 July, 2013, in the city of Porto, Portugal. It was jointly organized by the Portuguese and Tunisian Territorial Committees of the ICO. The event was collocated with RIAO/OPTILAS 2013.

The event attracted over 210 participants, including 68 students, with 140 submitted works including 31 invited presentations, 5 workshops, 3 hands-on activities, 1 short course, a poster session and two special sessions run jointly with RIAO/OPTILAS2013 conference (Entrepreneurship in Optics & Photonics session and Women & Optics session). It was the first ever ETOP event of this scale at which we were able to actively engage with and reach out to a wider range of delegates from 38 countries Additionally, the conference served as a forum for representatives from academia and industry as well as students and school teachers to interact and build bridges. The different sessions provided the framework of wider discussions on how to improve education, training and teaching in the field of optics and photonics. Lively discussions and debate not only during the interactive sessions but also around the coffee tables and during the social program in informal ways complemented the success of the conference open the way to the editions to follow.

9188-2, Session 1

Developing a photonics education program at college level from the ground up

Anca L. Sala, Baker College (United States)

The state of Michigan has a rich optics and photonics tradition and world-class universities undergoing research and graduating numerous Master and PhD students every year in these areas. The situation is very different at college level where a lack of photonics programs results in very few well prepared photonics technicians ready to contribute to the vibrant photonics private sector in Michigan and the Midwest. To alleviate this, a new two-year photonics program started in fall 2013 at Baker College, the only program of its kind in the state. The program is leveraging support from several sources, including the newly formed Mi-Light, the Michigan Photonics Cluster; OP-TEC, the NSF supported National Center for Optics and Photonics Education; and an NSF Project Grant awarded to the College. In its first year the photonics program has achieved several important milestones - among these are convening an Advisory Board with industry participation, developing almost the entire curriculum, and creating a fully functional optics and photonics laboratory providing students with hands-on training to complement the theoretical knowledge. Outreach activities are an integral part of the program. The College has been offering week long summer camps for high school students for the past five years and has introduced photonics activities in the most recent camp. Future plans include organizing a conference to promote photonics education programs to community and technical colleges in the state. The paper will describe the steps taken to introduce the new program and the lessons learned along the way.

9188-3, Session 1

Optical engineering capstone design projects with industry sponsors

Robert M. Bunch, Paul O. Leisher, Sergio C. Granieri, Rose-Hulman Institute of Technology (United States)

Capstone senior design is the culmination of a student's undergraduate engineering education that prepares them for engineering practice. In fact, any engineering degree program that pursues accreditation by the Engineering Accreditation Commission of ABET must contain "a major design experience based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints." At Rose-Hulman, we offer an interdisciplinary Optical Engineering / Engineering Physics senior design curriculum that meets this requirement. Part of this curriculum is a two-course sequence where students work in teams on a design project leading to a functional prototype. The students begin work on their capstone project during the first week of their senior year. The courses are deliverable-driven and the students are held accountable for regular technical progress through weekly updates with their faculty advisor and mid-term design reviews. We have found that client-sponsored projects offer students an enriched engineering design experience as it ensures consideration of constraints and standards requirements similar to those that they will encounter as working engineers. Further, client-sponsored projects provide teams with an opportunity for regular customer interactions which help shape the product design. The process that we follow in both soliciting and helping to scope appropriate industry-related design projects will be described. In addition, an outline of the capstone course structure as well as methods used to hold teams accountable for technical milestones will be discussed. Illustrative examples of past projects will be provided.

9188-4, Session 1

NanoJapan--International research experience for undergraduates program: Fostering U.S.-Japan research collaborations in terahertz science and technology of nanostructures

Sarah R. Phillips, Rice Univ. (United States); Cheryl M. Matherly, The Univ. of Tulsa (United States); Junichiro Kono, Rice Univ. (United States)

The international nature of science and engineering research demands that students have the skills necessary to collaborate internationally. However, limited options exist for undergraduates in science and engineering who want to pursue research abroad. The NanoJapan IREU Program is an innovative response to this need, which was developed to foster research and international engagement among young undergraduate students.

Funded by an NSF Partnerships for International Research and Education (PIRE) grant, each summer we send 12 U.S. students to collaborating labs in Japan, world leaders in terahertz (THz) spectroscopy, nanophotonics, and ultrafast optics. The students participate in cutting-edge research projects managed within the framework of the U.S-Japan PIRE collaboration. One of our focus topics is THz nanoscience (or TeraNano), which investigates the physics and applications of THz phenomena in nanosystems. Some of the ongoing research projects include amplifying THz waves in optically pumped graphene, polarization-dependent THz spectroscopy of aligned single-wall carbon nanotubes, growth and optical characterization of carbon nanotube solar cells, and THz detection using a nanoconstriction in a two-dimensional electron gas.

We will introduce the program model, with specific emphasis on designing high quality international student research experiences. We will specifically address the program curriculum that introduces students to THz research, Japanese language, and intercultural communications, in preparation for work in their labs. Ultimately, the program aims to increase the number of U.S. students who choose to pursue graduate study in this field, while cultivating a generation of globally aware engineers and scientists who are prepared for international research collaboration.

9188-5, Session 1

Learner-centered teaching in the college science classroom: a practical guide for teaching assistants, instructors, and professors

Margaret Z. Dominguez, Shelby D. Vorndran, The Univ. of Arizona (United States)

The Office of Instruction and Assessment at the University of Arizona currently offers a Certificate in College Teaching Program. The objective of this program is to develop the competencies necessary to teach effectively in higher education today, with an emphasis on learner-centered teaching. This type of teaching methodology has repeatedly shown to have superior effects compared to traditional teacher-centered approaches. The success of this approach has been proven in both short term and long term teaching scenarios. Students have to actively participate in class, which allows for the development of depth of understanding, acquisition of critical thinking, and problem-solving skills. As Optical Science graduate students completing the teaching program certificate, we taught a recitation class for OPTI 370: Photonics and Lasers for two consecutive years. The recitation was an optional 1-hour long session to supplement the course lectures. This recitation received positive feedback and learner-centered teaching was shown to be a successful method for engaging students in science, specifically in optical sciences following an inquiry driven format. This paper is intended as a guide for interactive, multifaceted teaching, due to the fact that there are a variety of learning styles found in every classroom. The techniques outlined can be implemented in many formats: a full course, recitation session, office hours and tutoring. This guide is practical and includes only the most effective and efficient strategies learned while also addressing the challenges faced. These struggles include formulating engaging questions, using wait time, encouraging shy students, covering a vast curriculum, and reaching out to large classrooms.

9188-6, Session 1

Hybrid education on optical design

Irina L. Livshits, Ilya Mimorov M.D., National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); H. P. Urbach, Technische Univ. Delft (Netherlands)

We discuss complexity and recent trends of interdisciplinary and internationalization on optical design education.

We've got big international and collaboration experience in the SMETHODS (www.smethods.eu) project in which optical design training sessions have been organized by a consortium of several European universities among which ITMO and TUD with funding by the European Commission. SMETHODS was targeted in particular to SME's, which often have no access to general optical design training in:

- imaging system, which has enormous importance for industry;
- non-imaging systems such as for illumination and solar applications;
- laser beam propagation and beam shaping through optical systems consisting of macroscopic elements and waveguides;
- diffractive elements of the size of the order of the wavelength.

The approach of ITMO and TUD is based on combination of in-room and e-learning education with sharing original courses and addition of complimentary disciplines. Given the large distance between the two institutes and the big progress in ICT, the most effective method of collaboration is using tools of e-learning. This is already true for traditional lectures in which a teacher explains the principles of the subject, but it is of course in particular true for practical exercises in optical design using computer software. In our case, adjustment syllabuses, education "logistic" and engineering support of the program become very important.

In this presentation we describe how e-learning is organized to realize shared education in optical design between ITMO and TUD.

9188-7, Session 2

Illuminating math with optics

Judith Donnelly, Three Rivers Community College (United States); Matthew Donnelly, Saint Bernard School (United States)

In spring 2012, a group of high school students took part in a problem-based learning workshop on laser safety. Students' reactions to the teaching method were extremely positive with some commenting that the exercise showed what math is "for". The students' math instructor (M. Donnelly) and one of the PBL instructors (J. Donnelly) sought and received funding from SPIE to continue the project to determine if engaging in "real world" exciting optics applications would improve student attitudes toward math instruction.

Pre-calculus is often one of the most difficult high school mathematics courses. As preparation for success in calculus, it is a somewhat disjointed presentation of concepts that often do not seem to have concrete applications. Optics applications were chosen to illustrate specific math concepts that students often find difficult. Since most students had not yet studied physics, the hands-on activities needed to be easy to explain in limited time.

During the first session (held at Three Rivers' campus), students measured attenuation in plastic optical fiber (logarithms) and transmittance of ND filters (exponents). Subsequent experiments in the high school classroom included diffraction gratings (trigonometry), matrix modeling of a crude lens (matrices) and conic sections. In each case, we emphasized the fun of optics, practicality of applications and necessity of math to make the applications work.

Three pre-calculus classes (total 45 students) took part in the program. Using a validated instrument, pre-post testing was conducted to determine changes in student attitudes toward math instruction over the course of the four-month program.

9188-8, Session 2

Discussion design in the course of applied optics: problems, thoughts, and extending

Zhaofeng Cen, Xiaotong Li, Zhenrong Zheng, Xiangdong Liu, Zhejiang Univ. (China)

Applied optics is a basic academic course for the students in optical engineering department. Now our course resources will be all online according to the plan of Education Ministry of China. This makes our students to find more and more correlated or uncorrelated study materials, and updates our class teaching. Due to the knowledge correlation in the course, from 2009 we have been organizing 4~6 study groups in each class every year and let our students discuss problems from simple to complex at the teaching progresses. A typical discussion problem which can connect the perfect optical systems and optical design is lens group combination and stop conjugate. From different angle of view such as light energy transmission, light information transferring, the discussion about this helps students to understand the relationship of pre-system and later system in field and aperture. We create a circumstance in which the students can share their difference thoughts at correlate problems and link them to develop their intelligence and knowledge. They learned to think different optical systems and to obtain the same technical characteristics about the mutual transformation between field and pupil, and find examples to prove their thoughts. Some reports of our students are shown in this paper. As shown by these that our students consider the problems of optical design using special and engineering brain and pay more attention to practical optical design after the discussion.

9188-9, Session 2

Optics and communication technology major of physics undergraduate degree at King Mongkut's Institute of Technology Ladkrabang

Prathan Buranasiri, King Mongkut's Institute of Technology Ladkrabang (Thailand)

Physics undergraduate degree major in optics and communication technology has been offered at King Mongkut's Institute of Technology Ladkrabang (KMITL), Bangkok, Thailand. The goal of the program is to graduate students, who would work in optics industry or continue to do optics research in graduate program both in physics and engineering degree. There are nine required three credit hour courses plus a number of selections in optics and communication base technology courses, which deal with fundamental optics, optical techniques, communication theory, and applications of optics in great details. Two three- hour laboratory courses, which are consists of experiment set emphasis on geometrical and physical optics, the generation and property of laser, Fourier optics, fiber optics, spectroscopy, etc. have been integrated in the required courses for more understanding in lecture courses and increasing in research technical skills. For improving self thinking and industrial working skills, nine credit hour research project, practical training or oversea studying have been including in the curriculum for students choosing in their final semester. Having real life research problems, the students who choose to do research project also have been allowed to conduct their research projects with private companies, industries, or research institutes. Moreover, the program has encouraged the students to participate in international conference as well. In order to make more participation opportunity for our students, recently, the program, on behalf of physics department, KMITL with supporting by NECTEC, SPIE and OSA, has organized its first optical science and engineering conference name "The international conference on Photonic solutions 2013 (ICPS 2013).

9188-10, Session 2

Digital devices: big challenge in color management

Oliver Vauderwange, Dan Curticapean, Paul Dressler, Peter Wozniak, Hochschule Offenburg (Germany)

The paper will present how the students learn to find technical solutions in color management by using adequate digital devices and recognize the specific upcoming tasks in this area. Several issues, problems and their solutions will be discussed. The scientific background offer specifically didactical solutions in this area of optics, color management and is the major items of this paper.

Color management is a crucial responsibility of media engineers and designers. Print, screen and mobile applications must independently display the same colors. Predictability and consistency in the color representation are the aims of a color management system. This is only possible in a standardized and audited production workflow.

Nowadays digital media have a fast-paced development process. An increasing number of different digital devices with different display sizes and display technologies are a great challenge for every color management system. The authors will present their experience in the field of color management. The design and development of a suitable learning environment with the required infrastructure is in the focus. With a composite form of theoretical and practical lectures a deeper understanding just in the area of the digital color representation is created.

9188-11, Session 3

Color science demonstration kit from open source hardware and software

Michael W. Zollers, Synopsys, Inc. (United States)

Color science is perhaps the most universally tangible discipline within the optical sciences for people of all ages. Excepting a small and relatively well-understood minority, we can see that the world around us consists of a multitude of colors; yet, describing the "what", "why", and "how" of these colors is not an easy task, especially without some sort of equally colorful visual aids. While static displays (e.g., poster boards, etc.) serve their purpose, there is a growing trend, aided by the recent permeation of small interactive devices into our society, for interactive and immersive learning. However, for the uninitiated, designing software and hardware for this purpose may not be within the purview of all optical scientists and engineers.

Enter open source. Open source "anything" are those tools and designs --hardware or software -- that are available and free to use, often without any restrictive licensing. Open source software may be familiar to some, but the open source hardware movement is relatively new. These are electronic circuit board designs that are provided for free and can be implemented in physical hardware by anyone. This movement has led to the availability of some relatively inexpensive, but quite capable, computing power for the creation of small devices.

This paper will showcase the design and implementation of the software and hardware that was used to create an interactive demonstration kit for color. Its purpose is to introduce and demonstrate the concepts of color spectra, additive color, color rendering, and metamers.

9188-12, Session 3

The laser propagation demonstration: a STEM-based outreach project

Mark F. Spencer, Michael J. Steinbock, Milo W. Hyde IV, Michael A. Marciniak, Air Force Institute of Technology (United States)

Investment in laser technology has led to significant advances in remote sensing, astronomy, industrial processing, and medical technology. To celebrate this rich heritage and promote public awareness in optics and photonics, the SPIE Student Chapter at the Air Force Institute of Technology (AFIT) developed the Laser Propagation Demonstration (LPD). This interactive demonstration serves as one of AFIT's legacy outreach projects for events involving education in science, technology, engineering, and mathematics (STEM). Initially developed with funding from a LaserFest grant awarded by SPIE in 2010, the goal was to develop a simple hands-on demonstration to highlight the optical effects of diffraction, refraction, and attenuation on laser propagation. Since then, the LPD has undergone several upgrades (thanks to the continued support from a 2012 SPIE Education Outreach Grant) to better highlight these optical phenomena and make it more engaging for a wider range of audiences. This paper celebrates the continued success of the LPD and shares the knowledge gained with an overview of its design and use in STEM-based outreach events.

9188-13, Session 3

Optics outreach evolves in southern California: OptoBotics begins to link informal to formal curriculum

Donn M. Silberman, PI (Physik Instrumente) L.P. (United States)

In the July 2013 issue of SPIE Professional Magazine, I was invited to and published an article related to this topic. This paper chronicles the progress made since that time and describes our direction towards bringing optics education from the informal programs we have provided for more than 10 years, to incorporating optics and photonics instruction into formal class curriculum. A major educational tool we are using was introduced at this conference two years ago and came to us from Eyest. The Photonics Explorer Kit has been used as a foundation during some OptoBotics courses and it has been provided, a long with a teacher training session, to 10 local high school science teachers in Orange County, CA. The goal of this first phase is to obtain feedback from the teachers as they use the materials in their formal classroom settings and after-school activities; such as science classes and robotics club activities. Results of the teachers' initial feedback will be reviewed and future directions outlined. One clear direction is to understand the changes that will be required to the kits to formally gain acceptance as part of the California state high school science curriculum. Another is to use the Photonics Explorer kits (and other similar tools) to teach students in robotics clubs 'how to give their robots eyes."

9188-14, Session 3

Microcontrollers and optical sensors for education in optics and photonics

Paul Dressler, Heinz-Hermann Wielage, Hochschule Offenburg (Germany); Ulrich Haiss, Offenburg University (Germany); Oliver Vauderwange, Peter Wozniak, Dan Curticapean, Hochschule Offenburg (Germany)

The digital revolution is going full steam ahead, with a constantly growing number of new devices providing a steady increase in complexity and power. Most of the success is based on one important invention: the microprocessor/microcontroller.

In this paper the authors present how to integrate microcontrollers and optical sensors in the curricula of media engineering by combining subjects of media technology, optics, information technology and media design. Hereby the aim is not to teach these topics separate from each other, but to bring them together in interdisciplinary lectures, projects and applications.

Microcontrollers can be applied in various ways to teach content from the fields of optics and photonics. They can be used to control LEDs, displays, light detectors and infrared sensors, which makes it possible to build measuring instruments like e.g. a lux meter, a light barrier or an optical distance meter.

The learning goals are to stimulate the student's interest in the multiplicity of subjects related to this course and to support a deeper understanding of the close connections between them. The teaching method that the authors describe in their paper turned out to be very successful, as the participants are motivated to bring in their own ideas for projects, they spend more time than requested and as many students return to the courses as tutors. It is an example for effectual knowledge transfer and exchange of ideas among students.

9188-15, Session 3

Increased Knowledge Transfer by Using Modern High-Speed Camera

Dan Curticapean, Peter Wozniak, Kai Israel, Oliver Vauderwange, Paul Dressler, Hochschule Offenburg (Germany)

A broad theoretical knowledge in Optics and Photonics is essential for media engineers. A combination of theory in the lectures augmented by practical work during the laboratory experiments forms the foundation of our gradual approach in communicating clearly and intensively all of the required topics. All laboratory experiments are guided but carried out by the students themselves and produced with a modern high-speed camera. This offers possibilities to analyze and iterate very fast phenomena. The slow motion footage makes it easily to analyze, to measure and to calculate certain sequences. This leads to a very intensive discussion regarding the provided topics and the used camera technology, resulting in a high standard knowledge transfer. Physics get now visible and more accessible for students.

This paper presents how the students execute and analyze experiments using modern technology. The results are prepared as media-friendly computer animation and video recordings.

9188-16, Session 4

Engaging the optics community in the development of informative, accessible resources focusing on careers

Anne-Sophie Poulin-Girard, Fanie Gingras, Univ. Laval (Canada); Véronique Zambon, Gabrielle Thériault, Ctr. d'Optique, Photonique et Laser (Canada)

Young people often have biased and pre-conceived ideas about scientists and engineers that can dissuade them from considering a career in optics. This situation is compounded by the fact that existing resources about careers in optics are not suitable since they mostly focus on more general occupations such as physicist and electrical engineer. In addition, the linguistic register is not adapted for students and many of these resources are only available to guidance counselors. To create appropriate resources that will inform high school students on different career opportunities in optics and photonics, we sought the collaboration of our local optics community. We selected seven specific occupations: entrepreneur in optics, university professor, teacher, technician, research and development engineer, sales representative and graduate student in optics. For each career, a list of daily tasks was created from the existing documentation by a guidance counselor and was validated by an expert working in the field of optics. Following a process of validation, we built surveys in which professionals were asked to vote for the tasks that

best represented their occupation. The surveys were also used to gather other information such as level of education and advice for young people who wish to pursue careers in optics. Over 175 professionals answered the surveys. With these results, we created a leaflet and career cards that are available online and depict the activities of people working in optics and photonics. We hope that these resources will help counter the negative bias against scientific careers and inform teenagers and young adults on making career choices that are better suited to their tastes and aspirations.

9188-17, Session 4

SPIE's school outreach activity program (SOAP) by IIT Madras SPIE student chapter: a review

Lavanya Kalikivayi, Indian Institute of Technology Madras (India) and KVKL (India); Venkataramana Kalikivayi, Udaya Kumar K., Ganesan A. R., Indian Institute of Technology Madras (India)

One of the important aspects of SPIE is "Community Support and Outreach Education", which should raise awareness and interest in optics and photonics among the targeted communities and school children. Hence as part of SPIE IIT Madras student chapter, we carried out SPIE SOAP, a 'School Outreach Activity Program'. Two types of schools were identified, one a high socio-economic status school and the other a low socio-economic status school having a majority of poor children. Optics related scientific experiments were demonstrated in these schools followed by oral quiz session to the students to assess the level of their knowledge before and after the experiments. We also clubbed this activity with "Vision Screening" and distribution of free spectacles for those children who live below poverty line. Out of the total children screened, 51.15% had normal vision, while 48.85% were found to have refractive errors where some of them could not even read the board. Treatable eye diseases were also found in 2.01% of the children. The entire activity is been discussed and documented in this paper.

9188-18, Session 4

Fun with optics: Outreach activity by Vidya Jyothi Institute of Technology student chapter

Badrinath Vadakkapattu Canthadai, Kumar Ravi, M. Esakki Muthu Raju, Vidya Jyothi Institute of Technology (India)

The SPIE and OSA student chapter of Vidya Jyothi Institute of Technology has been jointly conducting 'Optics Education and Outreach' activities for underprivileged children at various educational institutions over the last 2 years. The primary aim is to create awareness by helping the children understand the basics of science in a better way and get them interested in it by conducting various fun activities. The focus has centered on reaching out to children between the ages of 8 to 14 years. We organize many events with talks, videos and workshops where children actively participate. Every activity includes interactive sessions, where we spend time answering their insightful queries or discussing their comments. At the end of every program we conduct a spot quiz and reward them for best answers and also provide a certificate for every participant. In this paper we attempt to present a few efficient methods we have tested and employed in conducting these programs. So far, this program has been well received by the children and the educational institutions. We hope to build on the experience gained so far and continue to improve as we reach out to more children in future. We would like to acknowledge SPIE and OSA for their continued financial support towards this outreach program.

9188-19, Session 4

Color: what, how, and why we see: a workshop curriculum for K-12 students and parents

Michael W. Zollers, G. Groot Gregory, Katherine W. Calabro, Synopsys, Inc. (United States)

Through the ongoing outreach activities of the NES/OSA, we have been invited on several occasions to present optics workshops to students of many ages and backgrounds. With a nearly-overwhelming plethora of optics topics that could be presented, we have decided to develop a curriculum on color science that can be presented as workshops. Color science was chosen due to the wealth of examples of the application of color within a student's culture, society, technology, and experiences.

The goal of the workshop is to teach basic color science by examining objects and events that the students can experience or interact with in their own lives. The curriculum can be scaled to match groups of different sizes and backgrounds as well as to fit within certain time constraints. Depending on logistics, a variety of hands-on demos can be presented, or the workshop can be fully tutorial-based. This curriculum has been presented several times and is constantly evolving based upon each experience.

In this paper, we present the portions of the curriculum that have been developed to date. We discuss considerations for adding or removing sections to meet specific workshop constraints. We will also present the evolution of the curriculum from inception to its current state, highlighting the lessons learned from each presentation of the curriculum.

9188-20, Session 4

A colorful approach to teaching optics

Nancy J. Magnani, Eastconn (United States); Judith Donnelly, Three Rivers Community College (United States)

In the traditional elementary classroom setting in the United States, the teacher teaches it "all," including science. This includes the fundamentals of light detailed in both the Connecticut state science standards and the Next Generation Science Standards (NGSS). In support of the science curriculum, we have partnered for many years to provide interesting and intriguing optics based workshops for students from 10-12 years old. These workshops provide lessons and materials that the classroom teacher does not have the time or background to teach or the funds for the materials.

These workshops have included: introducing the light spectrum by making and taking home spectroscopes; understanding reflection by making a kaleidoscope; and gelatin optics to learn the principals of refraction. Though always appreciated by the teachers and enjoyed by the students, these lessons have become routine. What can be done to introduce a new approach to teaching the principals of light and photonics to young children?

Starting with lessons about color, students read books such as Hello, Red Fox, by Eric Carle and An Eye for Color: the Story of Josef Albers by Natasha Wing and then created their own "homage to a square" art work. Students studied examples of still life painting which demonstrated refraction and painted their own still life. Creating polarized light art is another lesson which teaches the fundamentals of optics through art. In this paper, we will explore the use of art to enhance the understanding of color and light phenomena.

9188-21, Session 4

Photonics meet digital art

Dan Curticapean, Kai Israel, Hochschule Offenburg (Germany)

The paper focuses on the work of an interdisciplinary project between photonics and digital art. The result is a poster collection dedicated to the International Year of Light 2015. In addition, an internet platform was created that presents the project. It can be accessed at http://www.magic-of-light.org/iyl2015/index.htm

From the idea to the final realization, milestones with tasks and steps will be presented in the paper. As an interdisciplinary project, students from technological degree programs were involved as well as art program students.

The 2015 Anniversaries: De Caus (1615), Fresnel (1815), Maxwell (1865), Einstein (1905), Penzias Wilson, Kao (1965) and their milestone contributions in optics and photonics will be highlighted.

9188-22, Session 4

Making a big difference in STEM education through the small world of nanoscience

Robert Gordon, Hitachi High Technologies America, Inc. (United States)

President Obama has made improving STEM education in the U.S. a focal point of his administration. From hosting science fairs at the White House to talking about the issue in front of a national audience during State of the Union speeches, the President has helped to keep this issue in the forefront, and he has called on government, educators and the business community to join him in reaching "a level of research and development that we haven't seen since the height of the space race." Across the country, educators and the business community are responding with innovative programs to improve student performance in these areas.

Hitachi High Technologies America, Inc. has answered the President's call to action with a program that is making the exciting world of nanoscience accessible to students from elementary school through graduate school. The program also provides teachers with lesson plans and learning modules they can use to teach students about electron microscopy and its applications. To reach as many students and educators as possible, Hitachi High Technologies America, Inc. has partnered with its distributors to bring advanced technology into classrooms across the country, and some of the leading nonprofit organizations whose mission is to improve STEM education in the U.S. Reflecting on his company's commitment to STEM education, HTA President Mr. Masahiro Miyazaki says, "We have been selling this product to industries, but we know that schools generally don't have access to this type of technology. So we decided that if we could bring the microscopes to the schools, it would really benefit STEM education and we could use this to support and contribute to society."

Conference 9189: Photonic Innovations and Solutions for Complex Environments and Systems (PISCES) II

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9189-1, Session 1

From vision to global market

Mohan R. Krishnan, Encell Technology, Inc. (United States)

Abstract – From Vision to Global Market

To come up with a company like Encell Technology you need to start out with an idea. Typically, a visionary who spawns this idea in the midst of numerous naysayers, does not just have an idea, he has the passion and visceral need to change the way the world looks at something and the potential for his idea to disrupt the status quo. The visionary usually seeks out others that not only have expertise in the field, but are flexible enough to think outside the box and buy into this vision.

Once the visionary sets his team in place there are three critical stages that need to take place to ensure the success of the company – money, the widget and wide acceptance.

Funding is the primary need for any start up – generally this is provided by family, friends and other acquaintances to seed the company. If lucky, an angel donor may participate, but more than likely institutional funding will become necessary after initial demonstration of the concept. This can be a daunting task as getting Venture Capital firms on board takes a great product, a great plan for the future, and an even greater salesman to get everyone excited about the opportunity. This has to be balanced with a need for secrecy in order to maintain an edge over any looming competition.

The second stage, which typically runs parallel to the funding stage, is the development of the widget. The widget needs to be unique and satisfy a previously unserved area or provide revolutionary improvements to an incumbent product. This involves the design and development of the widget so that it can be appropriately demonstrated and marketed. This will be your 'product' that is going to the customer.

The last and most important stage is making sure that the right customers and parties are courted for your product. This is critical as it will determine whether the whole venture gets off the ground or ultimately fails. A marquee customer gives instant credibility and can be responsible for the successful launch of the product. This is where the company's ability to execute on its promises and potential are put to a full test.

9189-2, Session 1

Photonics research at GTRI

Robert McGrath, Brent K. Wagner, Georgia Institute of Technology (United States); Grady Tuell, Georgia Tech Research Institute (United States)

The Georgia Tech Research Institute has long been involved in optical and photonics research and development. Work has covered the full gamut of scales from basic materials and engineered materials to devices and systems. Applications range from environmental monitoring to many DoE and DHS applications including chemical, biological and radiation sensing.

Examples of innovation in basic materials development and optical system development for environmental and homeland security monitoring will be highlighted.

Engineered nano-based optical materials under development will be discussed as potential low cost and robust replacements for traditional single crystal or particulate based materials used for radiation detection. These materials have applications ranging from high resolution medical imaging to inexpensive and ubiquitous radiation sensors in environmental and security applications.

At the system level, GTRI has also been developing innovative LIDAR technology for 28 years, with the mission of making laser remote sensing eye safe, rugged, light weight and cost effective. This has included the development of advanced optical solutions for monitoring air quality (ozone, particulate matter), wide-area sensors related to greenhouse gases (carbon dioxide, methane, and nitrous oxide), and LIDAR systems to support field testing of military electro-optical systems. In addition, GTRI researchers are actively engaged in the development of smaller, lighter, faster lasers to support intelligence, surveillance, and reconnaissance applications. In this area we are developing mixed mode computing architectures supporting real-time conditioning and processing of linear mode, waveform resolved systems, and are developing novel telescope and pointing optics for such systems.

9189-3, Session 1

The academic patent process: pitfalls and occasional home runs

Susan D. Allen, Embry-Riddle Aeronautical Univ. (United States)

Universities are increasingly seen as engines of innovation with patents as one of the main benchmarks of that innovation. Why should a faculty member bother to patent an innovative technology? When should it be patented? What is the process? Who decides whether to patent a technology or not? How much does it cost? How are patents and patents pending marketed? What is the average return on investment? Should patents count toward promotion and tenure? These and other questions will be addressed in the context of the average university tech transfer office.

9189-4, Session 1

From research to product: a complex pathway

François R. Flory, Institut Matériaux Microélectronique Nanosciences de Provence (France); Katia Mirochnitchenko, Pôle Optique et Photonique sud (France)

Scientific and technical innovations take place in many laboratories. There can be a lot of ground to cover from an innovative concept to an industrial product commercialized by a company. Different processes have been implemented in France to develop a real ecosystem to facilitate this process. Photonics clusters, incubators, start-up nurseries and technology transfer structures are working together with funding structures like business angels and with some public support. To illustrate the process, an example of a photonics concept applied to develop accurate and selective gas sensors will also be presented along with the approach used.

9189-5, Session 2

Knowhow-transfer between industry sectors through small engineering firms

Bernhard Michel, Hembach Photonik GmbH (Germany)

Research and development activities of larger commercial enterprises in optics and photonics are commonly very specific for the industry-sector. In contrast, the know-how of small engineering firms is often not sector-specific, but method-oriented. Additionally, these firms frequently have in-depth knowledge in a highly specialized field. Both facts empower them in transferring knowledge between industrial sectors and thus generating innovation. The author, managing director of a German engineering firm, demonstrates this in two examples: the knowledge about light scattering transferred between measuring technology,

biomedical optics and illumination engineering, and the knowledge transfer accomplished through optical design services.

9189-6, Session 2

Medical imaging and computers in the diagnosis of breast cancer

Maryellen L. Giger, The Univ. of Chicago (United States)

Quantitative image analysis (QIA) and computer-aided diagnosis (CAD) methods (i.e., computerized methods of analyzing digital breast images: mammograms, ultrasound, and magnetic resonance images) can yield novel image-based tumor characteristics (i.e., signatures that may ultimately contribute to the design of patient-specific breast cancer treatments). The role of QIA continues to grow. With computer-aided detection (CAD) of breast cancer, the aim was to provide a 'second opinion' to aid the radiologist in locating suspicious regions within screening mammograms. Today, the role of QIA/CAD is expanding beyond screening programs towards applications in risk assessment, diagnosis, prognosis, and response to therapy as well as in data mining to discover relationships of lesion characteristics as they apply to disease states. With QIA, computerized methods are being developed to (a) quantitatively characterize the features of a suspicious region or tumor, e.g., those describing tumor morphology or function, (b) merge the relevant features into diagnostic, prognostic, or predictive image-based biomarkers, (c) estimate the probability of a particular disease state, (d) retrieve similar cases, (e) compare the tumor in question to thousands of other breast tumors, and (f) explore the complex relationships among image-based tumor characteristics across large populations and association studies between the image-based signatures (i.e, image-based phenotypes) and histological/genomic data for imaging genomics.

9189-7, Session 2

Silicon carbide novel optical sensor for combustion systems and nuclear reactors

Geunsik Lim, Aravinda Kar, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Crystalline silicon carbide is a wide bandgap semiconductor material with excellent optical properties, chemical inertnes, radiation hardness and high mechanical strength at high temperatures. It is an excellent material platform for sensor applications in harsh environments such as combustion systems and nuclear reactors. A laser doping technique is used to fabricate SiC sensors for different combustion gases such as CO2, CO, NO and NO2. The sensor operates based on the principle of semiconductor optics, producing optical signal in contrast to conventional electrical sensors that produces electrical signal. The sensor response is measured with a low power He-Ne or diode laser.

9189-8, Session 2

The future is for plastic optoelectronics

Zakya H. Kafafi, National Science Foundation (United States) and Lehigh Univ. (United States)

The 21st century is witnessing a revolution in the area of electronics and photonics. Conventional semiconductor technology is being challenged by potentially inexpensive, flexible, and light-weight organic electronic, optoelectronic and photonic devices. In this talk I will review recent progress achieved for organic light-emitting diodes and organic photovoltaics on flexible substrates. These devices offer potential technological impact that will revolutionize the world of flat panel displays, solid state lighting and solar energy.

9189-9, Session 3

ChromaID: looking for nature's fingerprint

Thomas A. Furness III, Ratlab LLC (United States) and Visualant, Inc. (United States) and Univ. of Washington (United States)

Point of entry security identification, passports, driver's licenses, and currency often require robust methods for determining the authenticity of that material. Nature provides a robust fingerprint for condensed matter in the form of the interaction of light though absorption and scattering. Typical methods for characterizing specimens in this way involve spectroscopy wherein broadband light is used to excite materials and the reflected, transmitted or emitted light is gathered and separated into wavelengths. The amount of energy at each wavelength becomes the spectral signature of that specimen. To do this across a broad spectral range of UV though NIR is difficult and can be expensive. Termed the ChromaID, the author has been pioneering a new method of characterizing matter by structuring light first then observing interactions with a simple photodetector. In this way low cost devices that operate across a broad spectrum can be customized to identify and characterize known materials. This invited talk will describe the ChromaID and some of the challenges and outcomes in its development along with prospects for future applications.

9189-10, Session 3

The Schmidt-Czerny-Turner spectrograph

Jason McClure, Princeton Instruments (United States)

Since the invention of the CCD detector in 1969 by George Smith and Willard Boyle, incremental innovations to the dispersive imaging spectrograph have slowly materialized in response the abounding advances in CCD detector technology. The modern Czerny-Turner type spectrograph, arguably the most commonly used instrument in optical spectroscopy, fails to uphold the ever increasing needs today's researchers demand, let alone tomorrow's. This paper discusses an innovative solution to the Czerny-Turner imaging spectrograph bridging a more than 20 year gap in development and understanding. A manifold of techniques in optical spectroscopy both advantaged and enabled by this innovation are expounded upon.

9189-11, Session 3

Line-edge roughness and the impact of stochastic processes on lithography scaling for Moore's law

Chris A. Mack, Lithoguru.com (United States)

Moore's Law, the idea that every two years or so chips double in complexity and the cost of a transistor is always in decline, has been the foundation of the semiconductor industry for nearly 50 years. The main technical force behind Moore's Law has been lithography scaling: shrinking of lithographic features at near-constant cost per unit area. With smaller feature size comes the need for better control of those sizes during manufacturing. Critical dimension and overlay control must scale in proportion to feature size, and has done so for the last 50 years.

But in the sub-50-nm feature size regime, a new problem has arisen: line-edge roughness due to the stochastic nature of the lithography process. Despite significant effort, this line-edge roughness has not scaled in proportion to feature size and is thus consuming an ever larger fraction of the feature size control budget. Projection of current trends predicts a collision course between lithography scaling needs and line-edge roughness reality. This paper will explore the physics of line-edge roughness generation, and what might be done to improve it. The principles involved can affect not just semiconductor manufacturing, but other areas of nanofabrication as well.

9189-12, Session 3

Technological innovations for a sustainable business model in the semiconductor industry

Harry J. Levinson, GLOBALFOUNDRIES Inc. (United States)

Because of the increased difficulty of continuing to maintain the price-per-transistor trend of Moore's Law, integrated circuit manufacturers are compelled to improve manufacturing efficiencies to reduce costs. Technological innovations are leading to manufacturing processes with reduced materials and electricity consumption, as means to such improved efficiencies. For example, a common process that today uses organic solvents to remove polymeric coatings from edges of silicon wafers can be replaced by a laser-ablation processes that significantly reduces solvent consumption and disposal. Improved process control not only increases manufacturing efficiencies but also enables the production of integrated circuits that consume less electricity and have higher performance.

9189-13, Session 4

Sun-, Earth-, and Moon-integrated simulation ray tracing for observation from space using ASAP(R)

Robert P. Breault, Breault Research Organization, Inc. (United States); Sug-Whan Kim, Yonsei Univ. (Korea, Republic of)

The Space Optics Laboratory at Yonsei University, Korea, and the Breault Research Organization, Tucson, Arizona, in cooperation with each other have put significant R&D efforts into large scale ray tracing techniques. This presentation describes a complex model that combines the sun, the earth and a space optical instrument in an orbit into a real scale non-sequential ray tracing computation using ASAPTM. The Sun is expressed as an emitting sphere light source of 695,500 km in diameter. The earth also a sphere wherein its components are expressed as target objects to be observed and defined with appropriate optical characteristics. They include the atmosphere, land and ocean elements, each having distinctive optical properties expressed by single or combined characteristics of refraction, reflection and scattering. The current model has the atmosphere consisting of 33 optical layers, the land with 6 different albedos and the ocean with sun glint characteristics implemented. Then a space based optical instrument is defined in an orbit of several hundreds to thousands of miles in altitude above the earth's surface. The imaging and radiometric performances of the instrument can be expressed almost simultaneously. We report some examples of a real life application results. We believe that this approach would bring a great process efficiency improvement, not only to the construction of space optical instrument, but also to the project scientists working on the instrument at all phases of a space mission.

9189-14, Session 4

Tackling the challenges of water resources management from space: A long-term perspective on satellite sensor networks and data fusion

Ni-Bin Chang, Univ. of Central Florida (United States)

Climate change and extreme weather events have resulted in diversified challenges on hydrological regimes affecting the water resources management quantitatively and qualitatively. While sporadic extreme weather events trigger many floods and droughts, urban growth and agricultural production have caused an influx of nutrients into many lakes and coastal bays, leading to many eutrophic zones. Frequent forest fires and tree diseases in watersheds altered land use and land cover resulting in higher Total Organic Concentrations (TOC) and turbidity in water body. With changing surface runoff, these conditions accelerated the formation of algal blooms, some of which are toxic due to the presence of Microcystis (a cyanobacteria), which produces the hepatotoxin microcystin. Higher total organic concentrations would cause trouble in chlorination during the drinking water treatment leading to the generation of more disinfection byproducts such as Trihalomethanes (TTHM), which is deemed a carcinogen. This presentation demonstrates the future perspective as to how to close the loop of hydrological balance assessment at the ground level using a suite of current and future satellites and delineate the prototype of a near real-time early warning system using Integrated Data Fusion and Mining (IDFM) techniques for water quality monitoring. During my talk, multiple current and future satellites, such as MERIS, Hyperion, ASTER, MODIS, Landsat, SMAP, SWOT, and Sentinel, will be woven together to form the next-generation satellite sensor network for meeting the challenges of global changes in 21st century.

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9190-1, Session 1

Accurate chromatic control and color rendering optimization in LED lighting systems using junction temperature feedback

Marco M. Sisto, Jonny Gauvin, INO (Canada)

Accurate color control of LED lighting systems is a challenging task: noticeable chromaticity shifts are commonly observed in mixed-color and phosphor converted LEDs due to intensity dimming. Furthermore, the emitted color varies with the LED temperature. We present a novel color control method for tri-chromatic and quadri-chromatic LEDs, which enable to set and maintain the LED emission at a target color, or combination of correlated color temperature (CCT) and intensity. The LED color point is maintained over variations in the LED junctions' temperatures and intensity dimming levels. The method does not require color feedback sensors, so to minimize system complexity and cost, but relies on estimation of the LED junctions' temperatures from the junction voltages. If operated with quadri-chromatic LEDs, the method allows meeting an additional optimization criterion: for example, the maximization of a color rendering metric like the Color Rendering Index (CRI) or the Color Quality Scale (CQS), thus providing a high quality and clarity of colors on the surface illuminated by the LED. We demonstrate the control of a RGBW LED at target D65 white point with CIELAB color difference metric ?Eab < 1 for simultaneous variations of flux from approximately 30 lm to 100 lm and LED heatsink temperature from 25°C to 60°C. In the same conditions, we demonstrate a CCT error <1%. Furthermore, the method allows varying the LED CCT from 5500K to 8000K while maintaining luminance within 1% of target. Further work is ongoing to evaluate the stability of the method over LED aging.

9190-2, Session 1

Investigation of correlation of LF power modulation of light in natural and artificial illumination situations and acoustic emission

Cornelius F. Hahlweg, Joachim Dörfler, bbw Hochschule (Germany)

In last year's meeting we discussed questions of perception and physiological effects of power modulation of light in conjunction with acoustic stimuli. Such combinations are found in entertainment shows, but also in certain working environments. To extend these studies a reference device for the anaylsis and recording of low frequency power modulation in arbitrary natural and artificial illumination situations was desirable, so a correlation with synchronously recorded acoustic signals is possible. A broadband spectrometer for analysis of the power modulation of light from fractions of an Hz up to several kHz versus the light wavelength of the visual spectrum was designed and tested. Special attention is drawn to the directivity of the optical reciever and the question of spatial averaging over the aperture. Beside the primary intention the gathered multispectral data sets can be used for identification of artificial light components in natural environments. The paper deals with design issues, questions of data represenation, processing and verification problems and delivers some representative experimental results.

9190-3, Session 1

LED illuminant on the ambient light

Anqing Liu, Sandipan Mishra, Michael Shur, Rensselaer Polytechnic Institute (United States)

We develop an approach for combining illuminance and spectral power distribution of the LED and ambient light and apply our technique for developing a table lamp compensating ambient fluorescent light; and for an LED camera flashlight balancing the illuminance contrast between object and background. Our method uses closed loop, multi-objective optimization comprising: (1) characterizing the lighting task by illuminance, correlated color temperature (CCT), and statistical color quality indices that include a set of Statistical Color Quality Metrics and the Color Rendition Index (CRI) implemented with indexes of S (saturation) or D (dulling); (2) Measure the illuminance and the spectrum of the ambient light on the target lighting surface, which might depend on all the sources proving illumination and on reflected light; (3) determining desired illuminance of the LED source on the target lighting surface; (4) calculating the desired luminous flux of the LED source according to the desired illuminance; (5) constituting the SPD of the LED source; (6) calculating the relative spectra counts of the LED source and the ambient light on the target lighting surface (7) calculating the CCT and statistical color quality indexes of the combined light; (8) repeating the above steps until the resulting SPD is close enough to the expectation. Using the above method, a LED table lamp has been designed, which works together with usual fluorescent ambient light and generates working lighting environment with high fidelity and high CCT (6000K). The spectrum and luminous flux of the LED lamp is automatically tunable with a change of the ambient light.

9190-4, Session 1

High efficiency LED driver based on optical feedback

Edgar Marti-Arbona, Arizona State Univ. (United States); Tino Copani, STMicroelectronics (Italy); Bertan Bakkaloglu, Sayfe Kiaei, Arizona State Univ. (United States)

Light emitting diodes (LEDs) offer durability, long life, and high efficiency that make them an excellent alternative for illumination applications. The efficiency of conventional drivers suffers from losses due to the current sensing method that they employ. In this paper, the LED array itself is used as an optical sensor by periodically measuring neighboring cells' light intensity, instead of employing the commonly used series current-sense resistor. The results of this approach show that it provides accurate compensation of the LED characteristics, with less than one lumen variation in illumination, stability in color (color shift over time as low as $\Delta E = 0.76$), and efficiency of up to 98.66%. The proposed sensor compensates for actual optical performance of the LED array and reduces aging effects compared to the approaches based in current measurement and control. The optical current-sensing method is a closed-loop feedback alternative, which improves the power efficiency of the LED driver by 3%. It maintains constant output illumination of the LED over time, and it utilizes a reduced number of components, thus extending the effective lifetime of LED-based devices.

9190-5, Session 1

Real time compensation of in aging effects in solid-state lighting

Mario Cappitelli, Airbus Deutschland (Germany); Jan Rincke Bleicken, Airbus Group Innovations (Germany)

All available Solid-State Lighting (SSL) systems like LED or OLED suffer from the burden of intrinsic and extrinsic aging effects. This aging effects lead to a degeneration of brightness and color inside the light source, which can be observed far before the failure time (D70). The paper shows a solution about a real time compensation system, which is able to compensate the color and brightness of a light system by optical sensing and real time optimization. This approach offers the opportunity

to operate independently from the implemented light source type and number of primary colors. The benefit is an enhancement in the overall quality and durability of the light source parameters and an elongation of the system use. The solution utilize a full color sensor and miniaturized embedded computing capabilities to ensure the dedicated performance. Compared to the cost of LED and OLED lighting systems, the overall benefits in quality justifies the additional costs.

9190-6, Session 2

A new lifetime estimation model for a quicker LED reliability prediction

Benoit H. Hamon, Philips France (France) and MINATEC (France); Laurent Mendizabal, MINATEC (France); Guy Feuillet, CEA-LETI (France); Adrien Gasse, MINATEC (France); Benoit Bataillou, Philips France (France)

Light emitting diodes are considered to be highly efficient and reliable compared to conventional light sources. For these reasons, in the last ten years, the interest in LEDs for general lighting has constantly grown. Today, lumen lifetime estimation (based on IES LM-80-08 and IES TM-21-11) requires aging of at least 6000 hours. In this paper, we propose a lifetime prediction model for LEDs which present specific failure modes. The model is based on flux and parasitic resistance depreciation. To build this model, hundred and fifty LEDs have been aged following 9 current-temperature aging conditions. Stress driving current was fixed between 350mA and 1A and ambient temperature between 85°C and 120°C. A cross study of electrical and optical parameters evolution has been conducted which reveals two main failure modes. The first one concerns lumen depreciation as already studied in previous works. The second relates to an increase of the leakage and non-radiative currents which lead to an abrupt failure of the LED. Models of lumen depreciation and leakage resistance depreciation have been implemented using both electrical and optical measurements. In this paper, the acceleration of these two depreciations with ambient temperature and driving current will be discussed. The combination of these acceleration factors has been used for quicker L70 predictions for LEDs which present an increase of leakage current during their lifetime.

9190-7, Session 2

Uncertainty analysis for chromaticity coordinates and luminous flux measurements of LEDs

Rui Qi, Soraa, Inc. (United States); David P. Bajorins, Orb Optronix, Inc. (United States)

This paper introduces an uncertainty analysis model and its experimental implementation for chromaticity coordinates and luminous flux measurements of light emitting-diode (LED) sources. The model applies the theory of a numerical method for color uncertainty. The modeling process follows the steps described in GUM for the determination of uncertainties. First, the mathematical functions for chromaticity coordinates and luminous flux are expressed according to the sphere calibration and the LED measurement procedures. The variables of the functions are the input quantities for the model and defined as uncertainty contributors, and luminous flux and chromaticity coordinates are the output quantities. Second, the uncertainty contributors are categorized for Type A and Type B evaluations. Contributors such as spectrometer wavelength and spectral value repeatability vary randomly, and thus their standard uncertainties are analyzed with Type A evaluation. The other contributors such as spectrometer wavelength offsets and stray light do not show random variation; thus, their standard uncertainties are estimated with Type B evaluation. Further, simple methods are developed for measuring the contributors from spectrometers and source-measure units (SMU). Third, the sensitivity coefficients for the uncertainty contributors are calculated based on the numerical method by calculating the output quantities with a change of the input quantities. Fourth, the output quantities' uncertainty contributions are calculated using the standard uncertainties and the sensitivity coefficients of their contributors. Finally, all the uncertainty contributions are combined, and the expanded uncertainty is obtained (K=2). The calculation for each step is conducted by a Matlab program.

9190-8, Session 2

Optical simulations of organic light-emitting diodes through a combination of rigorous electromagnetic solvers and Monte Carlo ray-tracing methods

Mayank Bahl, Guirong Zhou, Evan Heller, William Cassarly, Mingming Jiang, Robert Scarmozzino, G. Groot Gregory, Synopsys, Inc. (United States)

Over the last two decades there has been extensive research done to improve the design of Light Emitting Diodes (LEDs) so as to enhance light extraction efficiency, improve beam shaping, and allow color tuning through techniques such as the use of patterned substrates, photonic crystal (PCs) gratings, back reflectors, surface texture, and phosphor down-conversion. Computational simulation has been an important tool for examining these increasingly complex designs. It has provided insights for improving LED performance as a result of its ability to explore limitations, predict solutions, and demonstrate theoretical results. Depending upon the focus of the design and scale of the problem, simulations are carried out using rigorous electromagnetic (EM) wave optics based techniques, such as finite-difference time-domain (FDTD) and rigorous coupled wave analysis (RCWA), or through ray optics based technique such as Monte Carlo ray-tracing. The former are typically used for modeling nanostructures on the LED die, and the latter for modeling encapsulating structures, die placement, back-reflection, and phosphor down-conversion. This paper presents the use of a mixed-level simulation approach which unifies the use of EM wave-level and ray-level tools. This approach uses rigorous EM wave based tools to characterize the nanostructured die and generate both a Bidirectional Scattering Distribution function (BSDF) and a far-field angular intensity distribution. These characteristics are then incorporated into the ray tracing simulator to obtain the overall performance. Such mixed-level approach allows for comprehensive modeling of the optical characteristic of LEDs and can potentially lead to more accurate performance than that from individual modeling tools alone.

9190-10, Session 2

Foil based optical elements for beam shaping and color homogenization of phosphor converted white LED sources

Franz-Peter Wenzl, Wolfgang Nemitz, Ladislav Kuna, Christian Sommer, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria); Paul Fulmek, Johann Nicolics, Technische Univ. Wien (Austria); Peter Pachler, Hans Hoschopf, Franz Schrank, TridonicAtco Optoelectronics GmbH (Austria); Gregor Langer, Austria Technologie & Systemtechnik Aktiengesellschaft (Austria); Paul Hartmann, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria)

Typically, light emission from light-emitting diodes (LEDs) occurs under a relatively broad range of angles. However, for a lot of applications a more directed light emission is desired. This can be realized by the use of additional optical elements, like lenses. However, this may lead to certain difficulties in case of light sources consisting of a plurality of individual LEDs, e.g., a panel light, which is dedicated to illuminate a target area homogenously. Instead of a homogeneous illumination, the use of lenses is prone to give reason for an inhomogeneous light distribution in which the emission from the individual LEDs is easily distinguishable. Therefore,

there is a strong request for alternative strategies of beam shaping of LED light in LED-luminaires targeting both on a directed as well as homogeneous illumination of an area.

In this contribution we discuss an alternative approach in this regard: Firstly, a collimator is designed, which strongly directs the light emitted from a single LED light source. Subsequently, a foil with an optical structure, which can be fabricated in a cost-effective way by Nanoimprint-Lithography and which diffuses the collimated light again, is applied on the collimator. The optical structure and the respective degree of light diffusion are designed in a way that the desired homogenization of the light emission both from a single as well as a plurality of LED sources can be realized. In addition, we show that the realization of a desired radiation profile is not the only advantage of such an approach. Another key benefit of this concept is the possibility to reduce the inhomogeneity of the CIE chromaticity coordinates of the emitted light, which frequently is observed in case that only a collimator is used.

9190-11, Session 3

Laser diodes in solid-state lighting *(Invited Paper)*

Jonathan J. Wierer Jr., Jeffrey Y. Tsao, Sandia National Labs. (United States)

There is increasing interest in III-nitride laser diodes (LDs) for solid-state lighting (SSL). This is due to various potential benefits over traditionally used light-emitting diodes (LEDs). First, LDs have directional emission, and therefore possess superior beam quality which enables new functionality in lighting systems and applications such as LD car headlights. Second, the narrow linewidths produced from an all LD white source theoretically provides the highest achievable luminous efficacies, and despite the narrow linewidth spectra have demonstrated high color rendering quality. Third, LDs could provide desirable features for smart lighting. These could include tunable chromaticities and color temperatures, control in time for digital communications and sensing, and control in space for high light-usage efficiencies. Finally, and maybe most importantly, LDs could be used to circumvent the drop in efficiency at high input powers that plagues III-nitride LEDs and forces operation at low input powers. For LDs above lasing threshold, the mechanisms responsible for this drop in efficiency are clamped, and therefore LDs have higher efficiencies at higher input powers compared to LEDs.

In this presentation, III-nitride LDs are explored as a next-generation light source for SSL. LDs and LEDs are compared in the areas of color rendering, efficiency, and economics for both state-of-the-art and future improved devices. Additionally, lighting systems and luminaire benefits are explored enabled by the LDs narrow linewidths and directional emission.

9190-12, Session 3

Laser-activated remote phosphor conversion with ceramic phosphors

Alan Lenef, John F. Kelso, Maxim Tchoul, OSRAM SYLVANIA Inc. (United States); Olvier Mehl, Joerg Sorg, OSRAM AG (Germany)

Direct laser activation of a remote phosphor, or LARP, is a highly effective approach for producing very high luminance solid-state light sources. Such sources have much smaller étendue than LEDs of similar power, thereby greatly increasing system luminous fluxes in projection and display applications. While several commercial products now employ LARP technology, most current configurations employ phosphor powders in silicone on rotating wheels to provide a low excitation duty cycle that helps limit quenching and thermal overload. These systems are already close to maximum achievable pump powers and intensities. To further increase power scaling and eliminate mechanical parts to achieve small footprints, OSRAM has been developing static LARP systems based on high-thermal conductivity monolithic ceramic phosphors. OSRAM has recently introduced a static LARP product using ceramic phosphor for endoscopy and also demonstrated a LARP concept for automotive forward lighting [1]. We first discuss the basic LARP concept with ceramic phosphors, showing how their improved thermal conductivity can achieve both high luminous fluxes and luminance in a static configuration. Secondly, we show the importance of scattering and low optical losses to achieving high overall efficiency and light extraction. This is shown through experimental results and radiation transport calculations. Finally, we discuss some of the fundamental factors which limit the ultimate luminance achievable with ceramic converted LARP, including optical pumping effects and thermal quenching.

[1] Tenth International Symposium on Automotive Lighting (ISAL) in Darmstadt, Germany (24 to 25 September 2013).

9190-13, Session 3

Fire-light LEDs for blue-balanced outdoor lighting

Pranciskus Vitta, Rimantas Vaicekauskas, Paulius Eidikas, Akvile Zabiliute, Rytis Stanikunas, Algimantas Svegzda, Arunas Tuzikas, Andrius Petrulis, Arturas Zukauskas, Vilnius Univ. (Lithuania)

The need for the improvement of the energy and functional efficiency of outdoor lighting has resulted in a massive replacement of high-pressure sodium (HPS) lamps by light-emitting diodes (LEDs). However, common white LEDs are blamed of the blue-enriched light, which disrupts circadian rhythms, increases light pollution, appears dimmer for elderly people, and poses aesthetic issues at low luminances. These drawbacks can be mitigated by using dichromatic (blue-amber) solid-state sources of light with blue-deficient spectrum. Here we report on such a "firelight" source, which is a cluster composed of direct-emission blue and phosphor converted amber LEDs, with a correlated color temperature of ~1860 K. The visual and non-visual performance characteristics of the firelight LED cluster have been assessed in the mesopic range of luminances typical of outdoor lighting. When compared to common white LEDs, the firelight LED cluster shows considerably reduced indices of melatonin suppression and skyglow, as well as somewhat increased retinal illuminance for elderly people. These advantages are counterbalanced by a reduced performance of perceiving colors, which, however, can be tolerated in many outdoor environments due to reduced color discrimination ability of the human vision at mesopic luminances. In comparison with almost metameric HPS lamp, the cluster exhibits similar reaction time and detection threshold of luminance contrasts for achromatic targets, but has somewhat smaller indices of melatonin suppression and skyglow, a potentially higher luminous efficacy and noticeably improved color rendering and color discrimination characteristics.

9190-14, Session 3

An imaging-based photometric and colorimetric measurement method for characterizing OLED panels for lighting applications

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The organic light-emitting diode (OLED) has demonstrated its novelty in displays and certain lighting applications. Similar to white light-emitting diode (LED) technology, it also holds the promise of saving energy. Even though the luminous efficacy values of OLED products have been steadily growing, their longevity is still not well understood. Furthermore, currently there is no industry standard for photometric and colorimetric testing, short- and long-term, for OLEDs. Each OLED manufacturer tests its OLED panels under different electrical and thermal conditions using different measurement methods. In this study, an imaging-based photometric and colorimetric measurement method for OLED panels was investigated. Unlike an LED that can be considered

as a point source, the OLED is a large form area source. Therefore, for an area source to satisfy lighting application needs, it is important that it maintains uniform light level and color properties across the emitting surface of the panel over a long period. The proposed study intends to develop a measurement procedure that can be used to test both short- and long-term flux and chromaticity properties of OLED panels. The photometric and colorimetric measurements will be made at different electrical and thermal stress conditions to understand sensitivity of flux and chromaticity properties to electrical and thermal parameter changes. Achieving a uniform thermal condition on the OLED panel throughout the testing period is more challenging than for an LED. Therefore, a special setup is needed to ensure proper thermal stability during the measurement period.

9190-15, Session 4

Understanding LED efficiency: reaching the limits via nano LEDs *(Invited Paper)*

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Efficiency is the key element for the solid state lighting revolution. To reach for the limits of LED technology we perform an in-depth analysis of the actual loss channels in an LED device starting with internal losses in the epitaxy, electrical losses due to chip architecture, as well as optical extraction and conversion losses. Based on recent experimental results we conclude that the dominant intrinsic loss channel in InGaN LEDs is the Auger process, the root-cause of the so called 'efficiency droop'. Self-consistent models are employed, to predict and optimize the efficiency of the LED device under different conditions of operation and stress, taking into account all major loss channels from Auger IQE–losses to phosphor heating via stokes losses. We find that the two dominant losses that still limit the LED efficacy are the internal losses due to the Auger effect at the one hand, as well as conversion losses due to quantum and Stokes losses on the other hand.

Based on this understanding we propose a novel concept for an integrated closely coupled nano-LED. Using laterally structured epitaxial layers comprising core shell nanorods in combination with sub-micron phosphor particles we combine internal efficiency gains via active area enlargement with highest conversions efficiency via closely coupled phosphor particles within the nanostructure. Leaving the standard path of lateral devices opens up a new world of opportunities in the realm of 3D nanostructures.

9190-16, Session 4

Comparison of extraction efficiency for thin-film flip-chip InGaN light-emitting diodes with microsphere and microconcave array structures

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The thin-film flip-chip (TFFC) light-emitting diodes (LEDs) are the state-of-the-art LED technology. Various approaches to enhance the light extraction efficiency have been implemented on TFFC GaN LED. Low-cost and practical method for enhancing the light extraction efficiency in TFFC GaN LED is important for the general illumination market. Recent work demonstrated the use of self-assembled colloidal microlens arrays by rapid convective deposition (RCD) method has resulted in significant enhancement in light extraction efficiency of conventional top-emitting GaN LED and organic LED.

In this work, comprehensive studies were carried out to investigate the light extraction efficiency of InGaN TFFC LEDs with microsphere arrays and microconcave array structures. The deposition of the colloidal microsphere arrays were achieved by deposition of TiO_2 microspheres employing RCD method. The formation of the lens arrays can be formed via binary deposition with high temperature annealing process. The PDMS microconcave array structure was obtained by imprinting method with convex template as the imprinting mold. The use of TiO_2 microsphere arrays on TFFC GaN-based LED results in light extraction of 75%, which corresponds to 3.7 times higher than that of TFFC LEDs with planar surface. The use of microlens arrays structure will enable further enhancement to 85%, which corresponds to 1.3 times higher than that of the state-of-the-art TFFC LED with surface roughness approach. Light extraction efficiency of 44% was achieved by employing PDMS concave structures on the top of TFFC LED. The key advantage of the self-assembled colloidal process is the ability for implementation of roll-to-roll printing method for large wafer scale manufacturing process.

9190-17, Session 4

Analysis of light extraction enhancement for nitride flip-chip light-emitting diodes with hybrid full-wave and ray-tracing method

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Light extraction efficiency of LEDs is limited by many effects. Many approaches only consider the light extraction efficiency inside LED chip, but have often overlooked the impact of chip efficiency caused by phosphor and packaging structure. A non-optimized white LED light source will cause the excitation blue light and emission yellow light to be absorbed by chip. Base on the above issues, a hybrid method for improving the light extraction efficiency of LEDs is presented. This hybrid method combines full-wave simulation which is used to analyze the scattering properties of structure sizes are on the order of the wavelength, and ray-tracing modeling for the interaction of light between layers inside LED chip and its package. According to this method, the light extraction and loss mechanisms in nitride flip-chip LEDs is studied. Consequently, we further develop their appropriate chip structures and packaging types.

9190-33, Session PWed

Lightweight LED Fluorescent lamp using engineering poly carbonate

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If the luminaries fall over, that can give a shock to anyone and the damage is much bigger while the lamps weight is larger. To prevent this, lightweight and unbreakable lamp was required for the fluorescent lamp. In this study, we developed lightweight fluorescent lamp using engineering poly carbonate as a heat sink instead of metal. In order to secure price competitiveness, we used double extrusion processes.

Thermally conductive plastic is used on the rear surface of the fluorescent lamp for emitting heat. And the diffuser plate was adopted on the front surface to prevent glare and light spread out in all directions. 100 2W LED were aligned as a light source. Converter is placed inside the fluorescent lamp so that there is no need to change the existing lamp housing. In order to use the power from both ends, there are two converters and each converter provides the power to 50 LEDs. Two extruders are combined at the single mold frame, therefore both the heat sink and diffuser are extrude simultaneously. Bending can be occurs due to the stress of different material binding during double extrusion. To prevent the bending, the composition of thermally conductive plastic is adjusted.

Fabricated fluorescent lamp has less than 20% of weight as compare to glass fluorescent lamp and power consumption is 18 watts, luminous efficacy 120 lm/W, respectively. Despite the heat conductive plastic is adopted, the system temperature is maintained less than 55? and the thermal resistance is 25 ?/W.

9190-34, Session PWed

Improved light extraction of nitride-based flip-chip light-emitting diodes by forming air voids on Ar-implanted sapphire substrate

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GaN-based flip-chip light emitting diodes (FC-LEDs) with embedded air voids grown on a selective-area Ar-implanted sapphire (SAS) substrate was demonstrated in this study. The proposed FC LED with an embedded light scattering layer can destroy the light interference and thereby increase the LEE of GaN-based flip-chip LEDs. The embedded light scattering layer made of void array was formed on the interface between the sapphire substrate and GaN underlying layer. The GaN-based epitaxial layers were grown through metal-organic vaporphase epitaxy on selective-area Ar-implanted AlN/sapphire(AIAS) substrates to form the void array .The epitaxial layers grown on Ar-implanted regions exhibited lower growth rates compared with those grown on implantation-free regions. Accordingly, air voids formed over the implanted regions after merging laterally grown GaN facet fronts. The light-output power of LEDs grown on SAS was greater than that of LEDs grown on implantation free sapphire substrates. At an injection current of 700 mA, the output power of LEDs grown on SAS was enhanced by 20% compared with those of LEDs without embedded air voids. The increase in output power was mainly attributed to the scattering of light around the air voids, which increased the probability of photons escaping from the LEDs. This study on FC LEDs with embedded light-scattering layer highlights the potential application of these LEDs as an alternative to conventional patterned sapphire substrates for improving the LEE of GaN/sapphire-based LEDs.

9190-35, Session PWed

Investigation of structure in the modular light pipe component for LED automotive lamp

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Light-Emitting Diodes (LEDs) have the advantages of small length, long lifetime, fast response time (?s), low voltage, good mechanical properties and environmental protection. Furthermore, LEDs could replace the halogen lamps to avoid the mercury pollution and economize the use of energy. Therefore, the LEDs could instead of the traditional lamp in the future and became an important light source. The proposal of this study was to investigate the effects of the structure and length of the light pipe component for a LED automotive lamp. The novel LED automotive lamp was assembled by several different modularization columnar light pipe. The optimized design of the different structure and the length to the light pipe was simulated by software TracePro. The design result must met the vehicle regulation of United Nations Economic Commission for Europe (UNECE) such as ECE-R19 etc. The structure of the light pipe could be designed by one, two or three stages structure. The length of the light pipe was studied from 60mm to 100mm. Then constitute the proper light pipe and choose different power LED to meet the luminous intensity of the vehicle regulation. The simulation result shows the proper structure and length has the best total luminous flux and a high luminous efficiency for the system. Also, the stray light could meet the vehicle regulation of ECE R19 Class F3. Finally, the experimental result of the selected structure and length of the light pipe could match the simulation result above 90%.

9190-36, Session PWed

Heat generation and thermo-mechanical effect modelling in longitudinally diode-pumped solid state lasers

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Thermal management in solid state laser is a challenge to the high power laser industry's ability to provide continued improvements in device and system performance. In this work an investigation of heat generation and thermo-mechanical effect in a high-power Nd:YAG and Yb:YAG cylindrical-type solid state laser pumped longitudinally with different power by fibre coupled laser diode is carried out by numerical simulation based on the finite element method (FEM). Impact of the dopant concentration on the power conversion efficiency is included in the simulation. The distribution of the temperature inside the lasing material is resolute according to the thermal conductivity. The thermo-mechanical effect is explored as a function of pump power in order to determine the maximum pumping power allowed to prevent the crystal's fracture. The presented simulations are in broad agreement with analytical solutions; provided that the boundary condition of the pump induced heat generation is accurately modelled.

9190-37, Session PWed

Realization of quantum dot-based polarized white LEDs using short-wavelength pass dichroic filters and reflective polarizer films

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This study introduces quantum dot (QD)-based polarized white light-emitting diodes (W-LEDs) combined with a short-wavelength pass dichroic filter (SPDF), which transmit blue wavelength regions and reflect yellow wavelength regions, and a reflective polarizer film (RPF)-sandwiched AgIn5S8-ZnS QD layer using an electrospray (e-spray) method. The AgIn5S8-ZnS QDs are good candidates for W-LEDs as a result of their broad emission band (~100 nm) from the donor-acceptor emission. The yellow emitting AgIn5S8-ZnS QDs are synthesized using a colloidal hot injection method and mixed with dimethylformamide (DMF), toluene, and poly(methyl methacrylate) (PMMA) for e-spray coating on the glass. Before the e-spray coating, the glass substrates are spin-coated with poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) in order to fabricate a conductive surface. The e-sprayed QD film is solvent annealed with chloroform in order to enhance its uniformity and transmittance. Furthermore, SPDFs are used instead of glass substrates to enhance the yellow emission from the QD layer. In order to realize the polarized light, the RPF is fabricated on the QD-coated glass and SPDFs. The AgIn5S8-ZnS QDs and QD films are characterized using photoluminescence (PL), electroluminescence (EL), and X-ray diffraction (XRD). For the realization of white light, a blue LED chip (?max = 450 nm) is used as the blue light source and an excitation source for the yellow QD film with an applied current of 60 mA. The EL intensity with an angular orientation of the polarizer is measured as a function of the polarizer-rotating angle from ?90° to 90° at 10° intervals.

9190-38, Session PWed

High Color Rendering Index of Remote-type White LEDs with Multi-Layered Quantum Dot-Phosphor Films and Short-Wavelength Pass Dichroic Filters.

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In this study, high color rendering index (CRI) white light-emitting diodes (W-LEDs) coated with red emitting (Sr,Ca)AlSiN3:Eu phosphors and yellow emitting AgIn5S8-ZnS quantum dots (QDs) on a glass or short-wavelength pass dichroic filter (SPDF), which transmit blue wavelength regions and reflect yellow wavelength regions, are introduced. The red emitting (Sr,Ca)AlSiN3:Eu phosphor film is coated on glass and SPDF using a screen printing method, and then the yellow emitting AgIn5S8-ZnS QDs are coated on the red phosphor (Sr,Ca)AlSiN3:Eu film-coated glass and SPDF using the electrospray (e-spray) method. In order to fabricate the red phosphor film, the optimum amount of phosphor is dispersed in a silicon binder to form a red phosphor paste. The AgIn5S8-ZnS QDs are mixed with dimethylformamide (DMF), toluene, and poly(methyl methacrylate) (PMMA) for the e-spray coating. The substrates are spin-coated with poly(3,4-ethylenedioxythiophene):p oly(styrenesulfonate) (PEDOT:PSS) in order to fabricate a conductive surface. The CRI of the white LEDs is improved through inserting the red phosphor film between the QD layer and glass substrate. Furthermore, the light intensities of the multi-layered phosphor films are enhanced through changing the glass substrate to the SPDF. The correlated color temperatures (CCTs) vary as a function of the phosphor concentration in the phosphor paste. The optical properties of the yellow AgIn5S8-ZnS QDs and red (Sr,Ca)AlSiN3:Eu phosphors are characterized using photoluminescence (PL), and the multi-layered QD-phosphor films are measured using an InGaN blue LED (?max = 450 nm) at 60 mA.

9190-39, Session PWed

Tri-wavelength single output Infrared LED based on QW area selective intermixing

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A monolithic tri-wavelength LED based on selective dielectric cap intermixing is investigated experimentally. It emits radiation with three wavelength peaks from three nearby regions of a single compact easy to fabricate QW structure. Each wavelength has an independent wavelength intensity power control, allowing the LED to emit a combination of one or more wavelengths at once from a single output. The device is divided into three selectively intermixed regions using an impurity-free vacancy induced intermixing technique. Each region is intermixed to varying extent resulting in different luminescence peaks. The bandgap energies of the selectively intermixed regions are blue shifted by amounts that depend on the thickness of a SiO2 capping film. The SiO2 film promotes the diffusion of Ga into that cap resulting in vacancies that migrate very quickly through the QW structure during rapid thermal annealing thereby inducing intermixing of the constituent atoms from the well and barrier materials. The fabrication process starts with a 400nm thick layer of SiO2¬ grown by plasma enhanced chemical vapor deposition (PECVD) over the whole sample. The three intermixed areas with different SiO2¬ thicknesses are defined via two photolithographic and subsequent reactive ion etching steps. The sample is then annealed at 975°C for 20s. Contact stripes are evaporated on each region to act as an independent intensity power control for that region. Experimental results showed a controllable 5nm, 11nm and 23nm wavelength blue shifts of the peak of the as grown electroluminescence spectrum corresponding to 0, 200nm, and 400nm SiO2 caps thicknesses respectively.

9190-40, Session PWed

Solution of multi-element LED light sources development automation problem

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Currently there is a necessity in reliable measurement and correct representation of energy, spectral and color parameters and characteristics of LED light sources applied in different fields of production. This explains by the swift development of LED products and creation of various kinds of multi-element sources based on LED technology. Such light sources might differ from each other, for example, by the color of light as well as by the location or by the number of emitters, etc. LED technologies have several advantages. But these technologies require a great attention, if it is needed to provide a certain character of lighting and / or color distribution at a predetermined distance (for example, in work area, area of analysis or observation).

To solve indicated problem a program was written. This program might be used for the calculation and representation of energy, color and spectral parameters and characteristics of light distribution both a separate LED light sources and multi-element light sources based on LEDs application.

This paper presents a description of the proposed program for the calculation and presentation of parameters and characteristics of separate and multi-element LED light sources. The description of the experimental results obtained for several types of LED light sources (different by the shape, by the location order of the emitting elements, by the energy characteristics and spectral distributions) is also represented.

The results can be used, for example, when developing:

- the multi-element light sources (linear , circular , etc.);

- adaptive lighting sources, with the spectral and color characteristics changing.

The present paper is a continuation of research of the group of authors in the area of creating problem-oriented lighting devices for optical-electronic systems, devices and industrial control systems in order to ensure optimal conditions for objects observation and analysis, as well as in the field of development of appropriate automated devices for measurement and control of radiation sources parameters and characteristics.

9190-41, Session PWed

Properties of InN epilayers grown at superatmospheric reactor pressures

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This contribution will presents the growth and layer analysis of InN epilayers grown by high pressure chemical vapor deposition (HPCDV) on c-plane sapphire and GaN/sapphire templates at different growth temperatures in the range of 800°C - 950°C at superatmospheric reactor pressures of 8 bar. The InN layers are analyzed by X-ray diffraction (XRD) and Raman spectroscopy to analyze the local and long range crystal ordering of the layers. Fourier transform infrared (FTIR) reflection spectroscopy was applied to evaluate the layer thickness, free carrier concentration, high frequency dielectric function, and carrier mobility for each layers of each sample, using a multi layer stack model. Photoluminescence (PL) spectroscopy studies where use to analyze the optical energy edge emission and its shift with free carrier concentration and intrinsic defects.

The FWHM of Raman E2(High) peak mode, 4.5 cm-1 for the epilayer grown on GaN/sapphire template at ~820°C, indicated good local crystalline ordering. This contribution will report on the free carrier concentrations and the PL emission shifts as function of the growth temperature, indicating a very sensitive relation between growth temperature and point defect density.

9190-42, Session PWed

Investigation of optical intensity in indoor visible light communication with different LEDs array

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The purpose of this study was look for the optimized design of light source array applied in indoor lighting combined with visible light communication system. The design of different light source arrays were simulated and compared, and actually be used in visible light communication system. There are three different light arrays: rectangular, radial and circle. The simulation result showed the rectangle array has the largest illumination flux than others. And its total flux was 2662.3 lm; maximum illumination was 338 lx and the effective illumination area of above 200 lx with a cover area of 2090 mm2. The measurement result also exhibited the rectangle array has the largest illumination flux than others. Its total luminous flux is 3538.9 lm and the effective illumination area of above 200 lx with a cover area of 2078 mm2. The measurement and simulation results have the same trend and the curve similarity was more than 99% by normalized cross correlation. In addition, when the distance of installed lamp was far from the wall of 1m, the rectangle array has the best illumination uniformity ratio of 63.5%. Finally, combined with the signal transfer analysis of visible light communication, a test system was built with the input signal frequency of 1k Hz and the transmission distance of 1.8m. The receive waveform of rectangle array was best in the transport of free space to other arrays and the divergence angle could reaches to 85°.

9190-43, Session PWed

New understandings of failure modes in SSL luminaires

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As SSL products are being rapidly introduced into the market, there is a need to develop testing protocols that can be performed quickly and provide data surrounding product lifetime and performance. These protocols, which can be derived from standard tests used by the electronics industry, are known as HALTs (highly accelerated life tests) and can be performed in a timeframe of weeks to months instead of years. Highly accelerated testing utilizes a combination of elevated temperature and humidity conditions as well as electrical power cycling to accelerate aging of the luminaires. In these studies, we report on the findings from HALT of entire luminaires. This approach has the advantage of jointly aging luminaire components as a whole including the housing, reflectors, diffusers, lenses, LEDs, and other electronics.

LEDs are typically considered the determining component for the rate of lumen depreciation. However, this study has shown that each luminaire component can independently or jointly influence system performance and reliability. Material choices, luminaire designs, and driver designs all have significant impacts on system reliability and lumen depreciation of a product. From recent data, the most common failure modes can be attributed to driver failures in capacitors and other electrical components, not the LED. In addition, reduction of light output as a result of materials aging in the lens, reflector or diffuser is common and begins much earlier in the process than lumen depreciation due to the LEDs. Insights into failure modes and occurrences as a result of HALTs will be reported with emphasis on comportment influence on overall system reliability.

9190-45, Session PWed

Study of photometric performance for standardization of LED lighting in agriculture

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With the increasing attention towards the fusion of green-IT and agriculture in the recent days, the light-emitting-diode (LED) plant factory has been receiving tremendous attention. Towards that end, two bands of light, which are effective for photosynthesis effect in plant i.e red (?red = 630 ~ 660 nm), and blue (?blue = 440 ~ 460 nm) are specifically used to grow plants in the artificial environment. However, the LED lighting products in agriculture have been developed imprudently without paying attention to the safety and performance concerns, which creates an urgent need for standardization of safety and performance of such products. In this paper, we report the evaluation and analysis of photometric properties of LED lighting towards the standardization of performance requirements in agriculture applications. The characterization setup consisted of blue and red LED chips used for LED illumination in agriculture, and the spectrum of those LED chips were confirmed to have peaks at 450 nm and 630 nm respectively. Using an integrating sphere, we measured photosynthetic photon flux density (PPFD) and photosynthetic photon efficiency, which are the two key indicators used in agriculture LED lighting. The measured value of PPFD was confirmed to be 15.4 ?mol?m-2?s-2 while that of photosynthetic photon efficiency was confirmed to be in 5 ?mol?m-2?s-2?W-2. We conclude that, unlike existing general LED lighting, the performance standards such as photosynthetic photon flux density and efficiency are important criteria in case of LED lighting for agriculture and are expected to be used as key indicators in their standardization.

9190-46, Session PWed

Characterize LED fluorescent replacement lamps using indirect light pathway

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Although LED lighting have recently used in variety of applications glare is considered as one of problems for realize LED in practical application. Glare phenomenon in LED light is caused by the strong direct emitting photon. The diffuser is often employed in order to eliminate this effect, but using diffuser results in reduce of luminous efficiency. In this paper, instead of using direct light with diffuser, we introduce a new approach by using indirect light pathway to reduce the effect of glare. To enhance the reflectivity of light as compared to conventional Al reflector, new designed reflector with high reflectorized paint has been adopted. Commercial light simulator has been used for design in order to maintain the light distribution. Outcoming results allow us to fabricate the product with glare of UGR15 and efficacy of 126.7 lm/W. Our designed product results in independent-UGR to position of the observer that was attributed to the unique shape of the light distribution. In addition, the Mg heat-sink technology was also used to achieve better heat dissipation. Consequently, heat-sink surface temperature decreases about 2.7 celsius degrees as compared to Al heat-sink. Designed structure with indirect light pathway and Mg heat-sink technology indicated high potential in reduction of glare phenomenon and promise to next generation of solid state LED lighting.

9190-19, Session 5

Complete Solid State Lighting Line at CEA LETI

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With a long experience in optoelectronics, CEA-LETI has focused on Light Emitting Diode (LED) lighting since 2006. Today, all the technical challenges in the implementation of GaN LED based solid state lighting (SSL) are addressed at CEA-LETI. First committed on basic research

of new LED technologies, as GaN nanowires (NWs) based LEDs, it has expanded its scope in SSL and Leti is now an R&D player throughout all the value chain of LED lighting.

The SSL Line at LETI first deals with the simulation of the active structures and LED devices. Then the growth is addressed: GaN nanowires but also 2D growths on sapphire or 8" silicon substrates. Using this material, technological steps are developed for the fabrication of LED dies with innovative architectures. For instance, Versatile LED Array Devices are currently being developed with a dedicated µLED technology. The objective in this case is to achieve monolithical LED arrays hybridized and interconnected through a silicon submount. In addition to the required bonding and 3D integration technologies new solutions for LED chip packaging, thermal management of LED lamps and luminaires are also addressed.

LETI is also active in Smart Lighting concepts which offer the possibility of new application fields for SSL technologies. An example is the recent development at CEA LETI of Visible Light Communication Technology also called LiFi. With this technology, we could demonstrate a transmission rate up to 10 Mb/s and the real time HD-Video transmission.

9190-20, Session 5

Optimization of optical systems for LED spot lights concerning the color uniformity

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The optimization of the system efficiency of LED spot lights is presented. The determined value for all systems is the color uniformity in the far field. LED spot light consists of a LED light source and a collimating secondary optic. Through angular or spatial separated emitted light from the source and the collimation with optical elements, a non uniform far field appears with colored rings, dots or patterns. The usage of scattering layers, facets and other elements can improve the color uniformity. However, additional elements lead to light losses and less collimated spots. Many feasible combinations result in very different spatial color distributions. Until now it has been difficult to make an objective evaluation of the color uniformity. For this purpose, the merit function Usl for color uniformity levels of spot lights was previously derived from human factor experiments.

In this optical simulation study, we use this merit function to tune LED spot lights with varied secondary optics to an equal color uniformity level. One multi colored LED light source is used as test light source for all simulations with the same power efficiency. It is combined with reflectors, TIR lenses and RXI optics in connection with several scattering elements. The systems are evaluated at the defined color uniformity in terms of luminous efficacy (lm/W), peak beam intensity, system volume and the needed scattering elements to reach the Usl value. The evaluation shows clear differences between the optical systems at the same color uniformity level.

9190-21, Session 5

A lighting metric for quantitative evaluation of accent lighting systems

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Accent lighting is critical for artwork and sculpture lighting in museums, and subject lighting for stage, film and television. The research problem of designing effective lighting in such settings has been revived recently with the rise of light-emitting-diode-based solid state lighting.

The problem of quantitatively assessing the effectiveness of a given accent lighting configuration is relatively unstudied. In the best cases, (e.g., museum lighting) lux measurements of the scene illuminance under different configurations are compared. However, to our knowledge, there is no easy-to-apply quantitative measure of the scene's visual quality as perceived by human viewers. In this work, we take first steps to explore this issue.

First, we consider a well-accent-lit scene as one which maximizes the information about the scene (in an information-theoretic sense) available to the user. We propose a metric based on both structural and color information, which are extracted from an image of the scene from the viewer's perspective. This metric is then calculated for varying lighting configurations in multiple scenes.

Preliminary results using computer graphics simulations and user studies suggest a good correlation between the proposed metric and human evaluation of lighting quality. Exceptions include scenes with glossy surfaces and high inter-reflection.

The proposed approach could enable future quantitative evaluation and semi-automatic design of accent lighting configurations.

9190-22, Session 5

Design a LED coupler to collocate with a light guide plate for illumination

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With progress in the LED luminous efficiency, the LED gradually expands the scope of application from the backlight to general lighting. In general lighting applications, various cleverly designed lenses or reflectors are used to form the required distribution of far-field light from the LED for general lighting. As for the application of the backlight, the light guide plate (LGP) is used to couple the LED light and emit the light uniformly on the surface to produce a uniform planar light source. The LGP has advantages such as slim volume, no LED light directly incident on eyes resulting in glare, etc., so the LGP is also adopted in general lighting applications. Because most LGP used for lighting do not collocate with the additional optical film, we obtain the prescribed distribution of the light emitting from the LGP substantially by adjusting the light emitting form the LED before it entering the LGP. Generally, this task is accomplished by the LED lenses or LED couplers. In this study we design the LED couplers for different purposes, for example: high collimated lighting, high coupling efficiency, high directionality, etc. Then, each type of LED coupler is optimized to obtain higher performance. Finally, through the design of the LED coupler the LED light is coupled into the LGP to produce uniform emitting light, which can be used as illuminator. All relevant simulation results are presented in this paper.

9190-23, Session 5

Smart restorative illumination of artwork and museum exhibits

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Polychromatic arrays of light-emitting diodes (LEDs) are capable of generating light with pre-defined chromaticity and color rendition properties. These light sources can be easily dimmed for an additional control the visual and non-visual effects of light. We report on a tetrachromatic solid-state light source with the smart control of chromaticity, color rendition properties, and photodamage potential. This light source could be used for restorative illumination of artwork and museum exhibits. The source contains an array of red, amber, green, and blue LEDs and a four-channel intelligent driver wirelessly controlled using a smart device. The control algorithm allows for instantaneous and continuous shifting, expanding, and shrinking the color gamut of the illuminated object while maintaining the photodamage potential of light at a constant value for different photosensitive materials (such as paper, paints, and textiles of different grades). This enables the dynamic and noninvasive adjustment of the visual appearance of artwork or museum exhibits with the safe selection of color temperature, partial

compensation of color fading, and removal of an unwanted tint due to aging. We demonstrate the application of the source for the restorative illumination of two objects. The first object is an aged pastel painting "restored" by compensating the substrate brownishing and expanding the color gamut to revive its lost shades. The second object is a gilded-silver medieval exhibit with the "restored" graying due to the diffusion of silver through a thin layer of gold. These two examples demonstrate the versatility of our approach for restorative and preserving illumination.

9190-9, Session 6

Numerical model to analyze phosphor layer heat transfer of an LED system

Indika U. Perera, Nadarajah Narendran, Rensselaer Polytechnic Institute (United States)

Solid-state lighting is advocated to be the future of white light illumination due to its promised high efficacy. The extraction of light from the light-emitting diode (LED) chip and the down-conversion material (phosphor) layer are paramount to achieving high efficacies. Remote-phosphor is one method that has improved light extraction via reduced light absorption at both the LED chip and phosphor layer. Thermal management at the LED chip has improved lumen maintenance by sustaining a lower LED operating temperature. The focus has now shifted to maintaining a lower operating temperature at the phosphor layer. Past research indicated that heat generated in the phosphor layer has negative effects on both short- and long-term performance of LED applications. At elevated temperature, reduced phosphor conversion efficiency contributes to increasing temperature, further increasing thermal degradation of the phosphor encapsulant. The absorption of light by the degraded phosphor encapsulant in turn reduces the phosphor conversion efficiency, further compounding the effect. Studies have illustrated that proper thermal management of the phosphor layer can reduce not only the peak temperature but also maintain a uniform temperature in the phosphor layer. The present study is concerned with analyzing the heat generation in the phosphor layer and the heat transfer along the phosphor layer on a more fundamental level with numerical modeling of the phosphor layer in an LED context. The contribution of heat conduction along the phosphor layer in addition to the heat dissipation of the phosphor layer to the ambient/surrounding by convection and thermal radiation will be presented.

9190-24, Session 6

High-thermal-stability white light-emitting-diodes employing broadband glass phosphor *(Invited Paper)*

Wood-Hi Cheng, Li-Yin Chen, Wei-Chih Cheng, National Sun Yat-Sen Univ. (Taiwan)

We report high-thermal-stability white light-emitting-diodes (WLEDs) employing broadband glass phosphors. The novel broadband phosphors exhibited high quantum-yield of 55.6% fabricated by dispersing multiple phosphors into SiO_2 based glass (SiO_2-Na_2O-Al_2O_3-CaO) at 680?. Through acceleration aging and thermal quench experiments, the acceleration factor and activation energy (Ea) of the glass phosphors have been well defined. The mean-time-to-failure (MTTF) evaluation of encapsulation materials of LED package showed the glass phosphors display 5 times better thermal stability than the silicone phosphors. The proof-of-concept of the WLEDs employing broadband phosphors presented high-quality cool-white light with tristimulus coordinates (x, y) = (0.358, 0.288), color-rending index (CRI) = 85, and correlated color temperature (CCT) = 3923K. The excellent thermal stability of the WLEDs is essentially beneficial to the applications for next-generation solid-state indoor lighting, especially in the area where high power and absolute reliability are required.

9190-25, Session 6

Eu3+ doped TiO2 nanospheres for GaN-based white light-emitting diodes

Peifen Zhu, Lehigh Univ. (United States); Hongyang Zhu, Jilin Univ. (China); Weiping Qin, Jinan Univ. (China); Chee-Keong Tan, Nelson Tansu, Lehigh Univ. (United States)

GaN-based white light-emitting diode (LED) is the technology of choice for solid state lighting. Commercialized white LED was obtained by coating an InGaN blue LED with a yellow-emitting phosphors (YAG: Ce^{3+}), which has led to its wide use in the various outdoor lighting applications. Despite their wide applications and high luminous efficacy, the disadvantage for white LEDs using only YAG: Ce^{3+} is related to high correlated color temperature (CCT) and low color rendering index (CRI), due to the lack of sufficient red spectral component. The resulting cool, bluish-white light makes such devices less desirable for indoor lighting, which requires lower CCT and high CRI.

In this work, the growth conditions of the Eu^{3+} doped TiO_2 spheres and its potential on GaN-based white LEDs were investigated. TiO_2 is promising phosphor host material due to its low cost, high transparency in the visible light regime, and good thermal, chemical, and mechanical properties. The use of anatase TiO_2 spheres is shown to result in significant enhancement in light extraction in GaN-based LEDs. TiO_2 spheres doped with Eu^{3+} can serve as red phosphor for GaN-based white LED applications to improve light extraction efficiency. The phase transformation condition was also investigated from amorphous TiO_2 to anatase TiO_2 and rutile TiO_2. The strong red emission peaking at 610 nm was observed under excitation of 464 nm and 397 nm for the Eu^{3+} doped anatase TiO_2 spheres. This finding points out the potential applications for Eu^{3+} doped TiO_2 in high efficiency white light emitting diode.

9190-26, Session 6

Fabrication and performance of dual-wavelength white light-emitting diodes assisted with red-emitting nanocrystals

Hong-Shuo Chen, National Central Univ. (Taiwan); Sheng-Shiun Chen, National Formosa Univ. (Taiwan); Kuan-Wen Wang, National Central Univ. (Taiwan); Shu-Ru Chung, National Formosa Univ. (Taiwan)

The yellow-emitting phosphor we use to be excited by blue chip has low color rendering index (CRI) and high correlated color temperature (CCT), due to the lack of the red light emission in the spectrum. Unfortunately, those phosphors are in micron size, resulting in not only have serious internal scattering and bad tunable wavelength but also have lower conversion efficacy, that cause the white light-emitting diode (WLED) luminous efficacy decreases with the addition micron phosphor. Therefore, in order to increase the luminous efficacy of WLED without losing CRI, the semiconductor nanocrystals (NCs) were used in this study. In order to exploring the characteristic of WLED devices, the blue chip was used as excitation source to pump the phosphors, which is blended the ternary alloyed red-emitting ZnCdSe NCs with the emission wavelength of 632 nm and quantum yield (QY) of 24 % in the green/red-emitting phosphors.

When the weight ratio of red-emitting phosphor ($CaSiAlN_3$:Eu) in the green-emitting phosphor ($Lu_3Al_5O_{12}$:Ce) increases from 0 to 11 wt%, the device performance such as the Commission International d'Eclairage (CIE) chromaticity coordinates shifts from (0.32,0.43) to (0.48,0.39), CRI increases from 64 to 81, and the luminous efficacy drops from 60 to 48 lm/W. The weight ratio of red-emitting phosphor is 5 wt% shows a better device performance with the CIE is (0.41,0.42), CRI is 81 and device efficacy is 53 lm/W. Therefore, we choose this recipe for further study. And then 3 wt% of ZnCdSe NCs is blended with the green/red-emitting phosphors (5 wt% red-emitting phosphor in green-emitting phosphor) not only increases 8 % of the luminous efficacy but increases 1 % of CRI compared to original green/red phosphor-based WLED.

9190-27, Session 6

Optical and thermal performance of a remote phosphor layer as a function of layer thickness

Xi Mou, Nadarajah Narendran, Yiting Zhu, Indika U. Perera, Rensselaer Polytechnic Institute (United States)

Down converting the short-wavelength radiation emitted by a wide bandgap LED is a popular technique for making white LED light sources. Commonly, the phosphor particles are dispersed close to the semiconductor die in a white LED package. However, in a remote phosphor package, the phosphor layer is placed some distance away from the die. Studies have shown greater photon extraction from remote phosphor white LED systems. Usually, the phosphor layers are created by embedding the phosphor particles in a binding medium such as epoxy or silicone. The light output characteristics of a remote phosphor system depend on several factors, including phosphor properties, phosphor concentrations in the binding medium, and optical and geometric properties of the binding medium of the phosphor layer. These factors can affect the light output and color properties of the white LED system. Furthermore, the properties of the phosphor and the binding medium and its geometric configuration can affect the heat buildup in the phosphor layer which can affect longevity. In the first part of this two-part study, an optical ray-tracing analysis will be carried out to quantify the luminous flux and the color properties of the white light and how they are affected when the thickness of the layer changes while holding the amount of phosphor constant. In the second part, a laboratory experiment will be conducted to verify the results and also to study how the phosphor layer temperature changes due to thickness change. The details of the study and the results will be presented.

9190-28, Session 6

The impact of individual materials parameters on color temperature reproducibility among phosphor converted LED sources

Susanne Schweitzer, Wolfgang Nemitz, Christian Sommer, Paul Hartmann, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria); Paul Fulmek, Johann Nicolics, Technische Univ. Wien (Austria); Peter Pachler, Hans Hoschopf, Franz Schrank, TridonicAtco Optoelectronics GmbH (Austria); Gregor Langer, Austria Technologie & Systemtechnik Aktiengesellschaft (Austria); Franz-Peter Wenzl, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria)

For a systematic approach to improve the white light quality of phosphor converted light-emitting diodes (LEDs) for general lighting applications it is imperative to get the individual sources of error for color temperature constancy under control. In this regard, it is imperative to understand how compositional, optical and thermal properties of the color conversion elements (CCE), which typically consist of phosphor particles embedded in a transparent matrix material, affect the constancy of a desired color temperature of a white LED source under operation. In this contribution we use an LED assembly consisting of an LED die mounted on a printed circuit board by chip-on-board technology and a flat CCE with a cuboidal shape mounted on its top as a model system and discuss the impact of potential sources for color temperature deviation among individual devices by means of optical simulations. Parameters that are investigated include imprecisions in the amount of materials deposition, deviations from the target value for the phosphor concentration in the matrix material, deviations from the target values for the particle sizes and optical constants of the phosphor material as well as deviations of the target values for the refractive indexes of phosphor and matrix material. From these studies, some general conclusions can be drawn which of these parameters has the largest impact and has to be controlled most precisely in regard of color temperature constancy among individual white LED sources.

9190-29, Session 7

Real-time InGaN growth monitoring during plasma-assisted MOCVD

Daniel Seidlitz, Rasanga L. Samaraweera, Georgia State Univ. (United States); Babar Hussain, Ian T. Ferguson, The Univ. of North Carolina at Charlotte (United States); Nikolaus Dietz, Georgia State Univ. (United States)

Further advances in the growth of indium-rich ternary group III-nitride alloys and heterostructures require a deeper understanding of the growth mechanism between dissimilar binaries with control strategies that allow tight control over compositional stability and thickness. Utilizing advances in optical characterization technologies, this contribution reports on the real-time monitoring of GaN and InGaN growth under MOCVD process conditions, applying plasma-emission spectroscopy (PES) and spectroscopy normal-incidence reflectance spectroscopy (NI-RS). The combination of PES and NI-RS enables the analysis of reactive nitrogen-containing gas phase species with growth surface deposition processes at a sub-monolayer level.

We will present real-time monitoring results on the growth of GaN and InGaN under migration-enhanced, remote-plasma MOCVD (MERP-MOCVD) reactor system with spatial and temporal controlled nitrogen-plasma, metalorganic (MO) and hydride precursor injection provisions. A hollow cathode plasma source is utilized to generate a active nitrogen/hydrogen plasma, which is fed by a 600W rf-power source. The reactive species (e.g. N*/NH*/H* fragments - analyzed by PES) are directed to the growth surface using the after glow regime of the remote plasma. The real-time monitoring data presented will be discussed for the GaN and gallium-rich InGaN process window as function of nitrogen/hydrogen plasma mixture, reactor pressure, substrate temperature, and rf-power setting, and compared with ex-situ optical and structural layer properties results.

9190-30, Session 7

Controlling the interband Auger recombination mechanism in III-nitride based ternary active regions

Chee-Keong Tan, Peifen Zhu, Nelson Tansu, Lehigh Univ. (United States)

Internal quantum efficiency deteriorates in III-Nitride light-emitting diodes (LEDs) when operating at high current density, hindering the progress for achieving high efficiency high-power LEDs. Various works pointed towards current injection efficiency quenching and Auger recombination as the limiting factors leading to the efficiency droop in LEDs. Recent studies revealed interband Auger recombination mechanism as an important source of efficiency droop in the InGaN quantum wells LEDs, which is highly influenced by alloy band structures. Describing the relationship between interband Auger recombination rate and the electronic band properties with a simple analytical relation is thus important for efficient band structure engineering to mitigate the interband Auger recombination in semiconductors.

In this work we employed analytical method to analyze the interband Auger recombination as a function of different band structure properties, and provide comparison of the interband Auger rates for both InGaN and dilute-As GaNAs active region materials. Dilute-As GaNAs alloy has been recognized for its potential as an alternative material for LEDs in green spectral regime. The interband Auger rates are analyzed in three different settings as follow: (a) band gap energy, (b) interband separation energy or energy difference between first and second conduction subbands, and (c) carrier effective masses. Our finding demonstrates the primary effect of energy band gap and interband separation energy, and the secondary effect of effective masses on the interband Auger recombination, suggesting the future directions of band-structure engineering to reduce the Auger rate. The comparison of interband Auger rates in the two III-Nitride-based semiconductors will be discussed.

9190-31, Session 7

Property analysis of InGaN layers grown by remote-plasma assisted MOCVD

Rasanga L. Samaraweera, Daniel Seidlitz, Indika M. Senevirathna, Georgia State Univ. (United States); Bahadir Kucukgok, Babar Hussain, Ian T. Ferguson, The Univ. of North Carolina at Charlotte (United States); Nikolaus Dietz, Georgia State Univ. (United States)

Ternary group III-nitrides possess a number of attractive physical, optical, and electronic properties that allow the fabrication of novel materials and device structures as outlined in various reviews. However, encountered problems in materials stabilization of indium-rich ternary and quarternary alloys limit the indium incorporation to a narrow composition range under presently deployed processing conditions. Therefore, several potential pathways to stabilize indium-rich group III-nitride alloys are presently explored, e.g. superatmospheric CVD processes or kinetic stabilized growth concepts such as plasma-assisted MBE. Recent advances in hollow cathode plasma source development enabled the plasma-assisted MOCVD growth of epitaxial GaN and InGaN at growth temperatures of 450°C -850°C with growth rates comparable to conventional MOCVD conditions.

In this contribution, we will present first results on the growth of GaN and InGaN epilayers under migration-enhanced, remote-plasma metalorganic chemical vapor deposition (MERP-MOCVD). The growth system is based on a rotating showerhead configuration with added provisions for spatial and temporal controlled injections of plasma, metalorganic (MO) and hydride precursor. The reactive nitrogen species (e.g. N*/NH*/H* fragments) generated by a hollow cathode plasma source are directed to the growth surface using the after glow regime of the remote plasma. GaN and gallium-rich InGaN layers and their physical properties will be presented and discussed as function of nitrogen/hydrogen plasma mixture, reactor pressure, substrate temperature, and rf-power setting. The layers have been characterized by x-ray diffraction (XRD), Raman spectroscopy, Fourier transform infrared (FTIR) reflectance and optical absorption spectroscopy.

9190-32, Session 7

Quantum efficiency improvement of InGaN/GaN LEDs using dual-metallic surface plasmon resonance

Ahmed Fadil, Technical Univ. of Denmark (Denmark); Yiyu Ou, Light Extraction ApS (Denmark); Daisuke Iida, Meijo Univ. (Japan); Haiyan Ou, Technical Univ. of Denmark (Denmark)

We have investigated an alternative approach of surface plasmon enhancement of InGaN/GaN LEDs using self-assembled nanoparticles. Although the resonance of self-assembled Ag nanoparticles can be controlled through the thickness of the pre-annealed Ag film, there will be only a single resonance peak centered on a specific wavelength, and the internal quantum efficiency (IQE) will be enhanced around this wavelength.

We are proposing a scheme whereby different regions of the LED spectrum can be enhanced when averaged over a micro-scale. This is done by having more than one resonance peak around which the IQE is enhanced.

One way of achieving this is by micro-scale variation between different metals, where the formed nanoparticles following thermal annealing will vary in size and/or metal type.

We have in this study considered two metals, Ag and Au, for this purpose, where the variation between the two types of metals is done through two steps of photolithography. The variation pattern is defined using a 6 µm period 2D array of 2x2 µm squares. Au deposition is made in the first step of photolithography, while the second step employs a pattern reversal to deposit Ag on regions without Au.

As the thermal annealing of Au is done at a higher temperature than that of Ag, the annealing of Au is done after the first lithography, before Ag deposition.

We have studied photoluminescence (PL) and absorption spectra of several samples with various combinations of Ag and Au thicknesses, and achieved PL enhancement using this approach.

9190-44, Session 7

Time-dependent cathodoluminescence from GaN modelled through a 2D diode

Eva M. Campo, Laurel J. Leigh, Bangor Univ. (United Kingdom); Milan Pophristic, Univ. of the Sciences (United States); Ian T. Ferguson, The Univ. of North Carolina at Charlotte (United States)

GaN is an important material for development of blue/green LED?s and lasers, due to its high stability and large band gap. To optimise device function and lifetime it is important to understand charging in the material and its effects on device behaviours. To this end, time-dependent cathodoluminescence (CL) has been correlated with specimen current (SC) and secondary electron emission (SEE). Two contributions to SC are identified graphically and it is seen that ambient conditions can radically alter SC dynamics.

Indeed, charge trapping was favourable in a humidity adsorbed scenario.

Interestingly, SE contrast could be reversed by the presence of a surficial layer of water molecules. Changes in CL, SEE and SC are attributed to the influence of hydrogen ions in the system, modulating band heights at a Au/GaN interface. A 2D diode model is presented to describe this process in time.

Irradiation was found not to be promoting redistribution of defects within the sample as deep level emissions were unaffected. At higher current densities, near-edge emission dynamics are comparable, suggesting a multitude of effects are responsible for quenching of CL - including surface adsorption and VGa activation, as recently published by Nykanen, APL, 2012.

9191-1, Session 1

Conditions for perfect focusing multiple point sources with the SMS design method *(Invited Paper)*

Pablo Benitez, Juan C. Miñano, Univ. Politécnica de Madrid (Spain) and Light Prescription Innovators, LLC (United States); Milena I. Nikolic, CeDInt-UPM (Spain); Jiayao Liu, Jose M. Infante, Univ. Politécnica de Madrid (Spain); Fabian Duerr, Vrije Univ. Brussel (Belgium)

In this work, we demonstrate how it is possible to sharply image multiple object points. The Simultaneous Multiple Surface (SMS) design method has usually been presented as a method to couple N wavefront pairs with N surfaces, but recent findings show that when using N surfaces, we can obtain M image points when N< M under certain conditions.

We present the evolution of SMS method, from its basics, to imaging two object points through one surface, the transition from two to three objet points obtained by increasing the parallelism, and getting to the designs of six surfaces imaging up to eight object points. All these designs are limited with the condition that the surfaces cannot be placed at the aperture stop.

In the process of maximizing the object points to sharp image, we try to exhaust the degrees of freedom of aspherics and freeforms. We conjecture that maximal SMS designs are very close to a good solution, hence using them as a starting point for the optimization will lead us faster to a final optical system. We suggest here different optimization strategies which combined with the SMS method are proven to give the best solution. Through the example of imaging with the high aspect ratio, we compare the results obtained optimizing the rotational lens and using a combination of SMS method and optimization, showing that the second approach is giving significantly smaller value of overall RMS spot diameter.

9191-2, Session 1

Thermodynamic limit for coherence-limited solar power conversion

Jeffrey M. Gordon, Heylal Mashaal, Ben-Gurion Univ. of the Negev (Israel)

The spatial coherence of solar beam radiation is a key constraint in solar rectenna conversion. Here, we present a derivation of the thermodynamic limit for coherence-limited solar power conversion – an expansion of Landsberg's elegant basic bound, originally limited to non-coherent converters at maximum flux concentration. First, we generalize Landsberg's work to arbitrary converter flux density. Then we derive how the values are further lowered for coherence-limited converters. The results do not depend on a particular conversion strategy. As such, they pertain to systems that span geometric to physical optics, as well as classical to quantum physics. Our findings indicate promising potential for solar rectenna conversion.

9191-3, Session 1

Excitation of multiple surface-plasmon-polariton waves guided by the interface of a photonic crystal and a two-dimensional gold grating

Liu Liu, Muhammad Faryad, Anthony S. Hall, Greg D. Barber, Thomas E. Mallouk, Akhlesh Lakhtakia, Theresa S. Mayer, The Pennsylvania State Univ. (United States)

The Floquet theory and the transfer-matrix approach were used to formulate the dispersion equation of surface-plasmon-polariton (SPP) waves guided by the planar interface of a one-dimensional photonic crystal (PC) and gold. The dielectric PC was taken to be made of silicon oxynitrides with a refractive index that varies periodically in the thickness direction. The Floquet-Bloch theorem was then applied to predict the excitation of multiple SPP waves when the PC partners a two-dimensional gold grating. That structure was also experimentally fabricated and characterized. The absorptance was measured and mapped against the wavelength and angle of incidence. The trace of high absorptance agreed well with the theoretical predictions. Both the theoretical and experimental results demonstrated broadband coupling of light of any polarization state over a large range of the angle of incidence. This structure can be potentially used as a planar solar concentrator, and our theoretical approach will help design optimal concentrators of that type.

9191-4, Session 2

Controlling light with freeform optics:

Recent progress in computational methods for optical design of freeform lenses with prescribed irradiance properties *(Invited Paper)*

Vladimir I. Oliker, Emory Univ. (United States); Boris Cherkasskiy, Sberbank Special Depositary (Russian Federation)

We will review the PDE, Optimization, and geometric methods for designing freeform refractive lenses for controlling light to achieve high energy efficiency. Computational difficulties connected primarily with very large number of constraints and efficiency requirements arising in developing reliable numerical solutions based on these methods will be discussed along with approaches to successfully resolve these difficulties. Our experience in dealing with these issues will be presented and illustrated by a test case of a lens design for which

extensive numerical simulations were carried out to test feasibility and validate its physical characteristics.

9191-5, Session 2

Tailoring free-form glass reflectors towards a homogeneous luminance distribution in roadway applications

Thomas Heßling, Marc C. Hübner, Ansgar Hellwig, Ulf Geyer, Christian Paßlick, Auer Lighting GmbH (Germany)

Free-form reflectors are encountered in numerous illumination systems, especially in highly sophisticated applications. The construction of this kind of optics however remains a challenging task where only a few methods are available to derive the free-form shape. One such method is the multi-ellipse approach where a superposition of conic sections is utilized to create the desired illuminance or luminous intensity distribution. While it is useful in many areas one is not always interested in an illuminance or intensity distribution. Especially street lighting reflectors are often tailored towards a homogeneous luminance, taking into account the road's reflective properties, luminaire arrangement etc.

While we used our implementation of the multi-ellipse method to design street lighting reflectors with a uniform illuminance before we now extended this method to support the calculation of a roadway reflector

with a homogeneous luminance. For a given roadway scenario we can quickly get an optimized reflector with a good performance compliant to roadway standards such as EN-13201 or IESNA-RP-8-00. Furthermore the optic can be quickly adapted to changing requirements. The method presented is suitable to be applied not only on roadway scenarios but all situations, where reflective optics are used to obtain specific light distributions.

9191-6, Session 2

Influence of manufacturing tolerances on efficiency of different solutions for collimating LED light flux

Mikhail A. Moiseev, Image Processing Systems Institute (Russian Federation) and Samara State Aerospace Univ. (Russian Federation) and LED Optics Design, LLC (Russian Federation); Egor V. Byzov, LED Optics Design, LLC (Russian Federation) and Image Processing Systems Institute (Russian Federation) and Samara State Aerospace Univ. (Russian Federation); Sergey V. Kravchenko, Image Processing Systems Institute (Russian Federation) and Samara State Aerospace Univ. (Russian Federation) and LED Optics Design, LLC (Russian Federation); Leonid L. Doskolovich, Image Processing Systems Institute (Russian Federation) and Samara State Aerospace Univ. (Russian Federation)

Light-emitting diodes (LEDs) become more and more popular light sources due to their advantages, such as compact size, high efficacy, long lifetime, resistance to vibration, shock etc. For optical design the most outstanding feature of LED is its small size that allows developing compact lighting devices which accurately and effectively generate the required light distribution redirecting the whole light flux from LED to illuminated region. All lighting devices can be divided in four groups by their beam angle: collimators, spotlights, medium-beam and wide-beam devices. Manufacturing of collimator's optical system demands the highest requirements to the tolerances.

In this paper several standard solutions for collimation of LED light flux are considered: parabolic mirror, TIR lens (lens with surface working on the total internal reflection principle) and Fresnel lens. All solutions are computed and investigated for the same problem and have similar characteristic dimensions. It is shown that while only TIR-lens collimates the whole LED light flux it does not provide the best performance. Tolerance analysis shows that real tolerances of injection molding process make TIR-lens the worse solution for light collimation. The second place takes parabolic reflector with medium value of beam angle and the best performance is provided by Fresnel lens with TIR relief.

9191-7, Session 3

Nonimaging optics in combined heat and power *(Invited Paper)*

Eli Yablonovitch, Univ. of California, Berkeley (United States); Roland Winston, Lun Jiang, Univ. of California, Merced (United States)

Nonimaging Opics and this film GaAs solar cells are combined in a novel way to produce electricity and high temperature heat.

9191-8, Session 3

Integrated design of solar thermal evacuated tubes using nonimaging optics

Lun Jiang, Roland Winston, Univ. of California, Merced (United States)

Integrated design for evacuated solar collectors using nonimaging optics have been receiving more attentions from the industrial applications. We are presenting the optics, system design and characterizations of such devices to validate its improvement over conventional solar evacuated tube design.

9191-9, Session 3

New directions for nonimaging optics; pushing the boundaries

Roland Winston, Lun Jiang, Univ. of California, Merced (United States)

Some important unsolved problems are suggested and new directions proposed

9191-10, Session 3

Light extraction efficiency in light emitting diodes (LEDs) for pyramidal geometry using light tools

Melissa N. Ricketts, Roland Winston, Univ. of California, Merced (United States)

Light extraction efficiency - the number of photons that escape a semiconductor substrate divided by the number of photons generated in the semiconductor substrate, is of crucial importance to improve the wall plug efficiency in LEDs. LED chip semiconductor substrates without alterations such as reflective coatings and rough surface etching demonstrate as low as 4% LEE. This generates a low wall plug efficiency. Here we look into improving the LEE via the introduction of pyramidal geometry to the surfaces of these substrates. We use ray tracing in Light Tools to analyze power input vs. power output while increasing the field of pyramids on our substrate surfaces. We expect to see larger light extraction efficiency as the surface pyramid count increases.Light extraction efficiency - the number of photons that escape a semiconductor substrate divided by the number of photons generated in the semiconductor substrate, is of crucial importance to improve the wall plug efficiency in LEDs. LED chip semiconductor substrates without alterations such as reflective coatings and rough surface etching demonstrate as low as 4% LEE. This generates a low wall plug efficiency. Here we look into improving the LEE via the introduction of pyramidal geometry to the surfaces of these substrates. We use ray tracing in Light Tools to analyze power input vs. power output while increasing the field of pyramids on our substrate surfaces. We expect to see larger light extraction efficiency as the surface pyramid count increases.

9191-11, Session 3

Nonimaging optics heats up Mongolian winter

Roland Winston, Bennett K. Widyolar, Lun Jiang, Univ. of California, Merced (United States)

In January, 2014 nonimaging technology was tested in the coldest, most polluted city in the world. High temperatures were achieved showing the way to replace coal burning with solar energy

9191-12, Session 4

Switchable transparency optical element for reactive solar tracking *(Invited Paper)*

Marco Stefancich, Harry Apostoleris, Carlo Maragliano, Matteo Chiesa, Masdar Institute of Science & Technology (United Arab Emirates)

Mechanical tracking needed for high concentrator photovoltaic systems limits their application to large ground mounted power plants.

Ability to design active optics, based on controllable modifications of the concentrator optics transfer function, allowing for mechanically stationary sun optical tracking, would open the larger rooftop mounted PV market allowing CPV to benefit from its potentially higher efficiency resulting in lower installation costs.

We discuss here a non-mechanical active optics providing a possible path for stationary tracking concentrator systems.

Christiansen's filters are based on the intermixing, at a scale larger than the wavelength of light, of two transparent media whose indexes of refraction coincide only in a limited spectral region, where the system is transparent. Outside this region multiple scattering at the interfaces between the media drastically reduces transmissivity.

Being able to control the index contrast between these two phases with an external control variable (e.g. temperature) allows designing a Christiansen's switch where the high index contrast state has high diffuse reflectance while the low contrast state is essentially transparent.

The large change in density in first order (solid-liquid) phase transitions is associated to a large refractive index change and opens, therefore, to the design of this kind of switch.

We will present the theoretical analysis and experimental evidence of a switchable transparency optical element and propose its coupling to a sun concentrating optics.

9191-13, Session 4

Angular confinement in solar cells: viable micro-optical designs

Jeffrey M. Gordon, Daniel Feuermann, Ben-Gurion Univ. of the Negev (Israel); Heylal Mashaal, Ben-Gurion Univ of the Negev (Israel)

Approaching the thermodynamic limit for photovoltaic conversion efficiency is contingent upon achieving equality between the respective angular ranges of (a) solar radiation incident on the cell and (b) emitted (luminesced) radiation, in a cell with negligible non-radiative recombination. The field of concentrator photovoltaics is predicated on maximizing the former (i.e., using an optical concentrator to transform radiation from the solar disk so as to cover essentially the entire hemisphere when it reaches the cell), while accepting cell luminescence as lambertian. The physics of the problem informs us that one could achieve the same efficiency boost by limiting the angular range of luminesced radiation to that of the solar disk, without any concentration. We present candidate maximum-performance micro-optical designs that can be an integral part of sub-millimeter coatings on solar cells, based on basic principles in radiative transfer and aplanatic optics. Both total-internal-reflection and mirrored units are considered, and their performance is compared to corresponding proposals published to date. Device dimensions permit analyses with geometric optics (i.e., via raytracing, with light transfer not being diffraction-limited).

9191-14, Session 4

Decentralized nonimaging micro-optical concentrator

Tian Gu, Univ. of Delaware (United States); William C. Sweatt, Sandia National Labs. (United States); Gautam Agrawal, Univ. of Delaware (United States); Bradley H. Jared, Ben J. Anderson, Ron S. Goeke, Brenton Elisberg, Scott M. Paap, Jose Luis Cruz-Campa, Vipin P. Gupta, Murat Okandan, Gregory N. Nielson, Sandia National Labs. (United States); Michael W. Haney, Univ. of Delaware (United States)

A novel non-imaging micro-concentrator concept and its development in Sandia National Lab's microsystems-enabled photovoltaics (MEPV) program are described in this paper. The MEPV project employs advanced micro-cell fabrication and novel micro-optic approaches for next generation photovoltaics, aiming at the SunShot PV system price target.

Key notions of the 2-element micro-optical concentrator are toroidal primary and secondary lens surfaces that generate donut-shaped illumination patterns on the secondary optics and the solar cell, respectively, which eliminates hot spots at the focal plane and potentially improves conversion efficiency. The secondary optical element further incorporates a reflective cone structure immersing the solar cell (250 microns in diameter) in order to enhance the concentration-acceptance angle product. The design procedure for such a micro-concentrator structure also takes into account factors such as fabrication (e.g., limited aspect ratio and depth of the reflective cone and rounded corners due to machine tools), temperature-dependent refractive index variances, thermo-mechanical effects of the optical materials, etc.. One optical design achieves a 600X geometric concentration with a ±2 degree (90% of peak) acceptance angle under AM1.5G, allowing low cost, mass production using injection molding.

For the first generation toroidal-cone concentrator array designed, polycarbonate and Sylgard 184 PDMS are chosen as the concentrator and filler materials, respectively. PDMS is used to fill the space between the primary and secondary optics in order to prevent moisture ingression. The optical concentrator has an entrance aperture and exit aperture of ~2.5mm and ~0.25mm in diameter, respectively, and a total thickness of ~5mm.

9191-15, Session 5

Luminescent manipulation of sunlight: leveraging low etendúe emission with nonimaging optics for photovoltaics and biofuels *(Invited Paper)*

Noel C. Giebink, The Pennsylvania State Univ. (United States)

Luminescent and nonimaging optical concentration have traditionally been pursued independently of one another owing to unrestricted luminescent etendúe. We are pursuing a hybrid approach, using simple photonic structure to control luminescent etendúe in order to exploit secondary nonimaging optical gain to increase concentration ratio for photovoltaics and alternatively to optimize the distribution of light within closed photobioreactors for enhanced algal biofuel productivity. This talk will present recent experimental results that demonstrate this approach using printed GaAs microcell photovoltaics together with modeling of the productivity improvement available for cyanobacteria in photobioreactors employing optimized luminescent redistribution.

9191-16, Session 5

Optimization of a spectrum splitter using differential evolution algorithm for solar cell applications

Li Fan, Univ. of Delaware (United States); Muhammad Faryad, Greg D. Barber, Thomas E. Mallouk, The Pennsylvania State Univ. (United States); Peter B. Monk, Univ. of Delaware (United States); Akhlesh Lakhtakia, The Pennsylvania State Univ. (United States)

A surface-relief grating made of dielectric materials was investigated for specularly transmitting one part of the solar spectrum while the other part was transmitted non-specularly. Two types of grating shapes were investigated: rectangular and circular. The transmittances and reflectances were computed using the rigorous coupled-wave approach. The geometry and the refractive indexes of the materials of the spectrum splitter were optimized using the differential evolution algorithm so that the specular and non-specular transmittances approach complementary

step functions while keeping the total reflectance very low throughout the solar spectrum. The period, depth, and duty cycle of the grating were optimized for obliquely incident unpolarized light and the AM1.5 solar spectrum was assumed. We found that that significant spectrum splitting can be achieved if the incidence angle is between zero and 15 degrees. The spectrum splitter can be used to spatially multiplex different solar cells that have high efficiency in mutually exclusive parts of the solar spectrum.

9191-18, Session 5

Design and analysis of holographic optical elements for daylighting interior of a building with solar radiation free from UV and IR

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Daylighting is an effective means of reducing both lighting and cooling costs of the buildings. Most of the conventional daylighting techniques are heavy and bulky, at the same time they require proper maintenance and adjustment for optimal performance. However, HOEs provide an effective method for even distribution of sunlight within a room. HOEs can function as gratings, lenses and dispersive system simultaneously. The main features of HOEs are thin film geometry, light weight and of low coast. HOEs are wavelength selective and can be used to filter out UV & IR. Thus a single holographic element can be used as beam deflector, spectral filter and their concentration. Another advantage is that HOE systems usually have no moving parts and requires low maintenance. HOE properties concerning light deflection can be exploited for the redirection of sunlight towards remote areas which do not have direct access to exteriors such as basements enabling their conversion to spaces with new spaces of increased value.

In present work theoretical design of holographic optical element has been done to filter out ultraviolet (UV), infrared (IR) solar radiation and to allow only visible spectrum to enter inside the interior of the room. Further it is also shown that by optimizing the processing parameters suitably holographic lenses may exhibit larger acceptance angle which will help to minimize solar tracking.Such system may provide even distribution of sunlight within interior of a building which is hygienic and supportive to human health and activities as well as reduces energy demand.

9191-19, Session 6

Light valve based on nonimaging optics with potential application in cold climate greenhouses

Angel A. Valerio, Michele A. Mossman, Lorne A. Whitehead, The Univ. of British Columbia (Canada)

We have designed, constructed and tested a variable light valve and thermal insulation system based on nonimaging optics. The system incorporates variably-nested compound parabolic concentrators and can readily be switched between a highly light transmissive state and a highly thermally insulating state. This variable light valve makes the transition between high thermal insulation and efficient light transmittance practical in a structure and may be useful in plant growth environments to provide both, adequate sunlight illumination and thermal insulation as needed.

We describe the optical design of the variable light valve, comparing ray-tracing simulation results and measurements of experimental devices to evaluate the system performance. We have measured light transmittance values exceeding 80% and achieved thermal insulation values substantially exceeding those of traditional energy efficient windows.

We describe a potential application for the light valve in high latitude and/or extreme weather greenhouse structures. The light valve system represents a potential solution for greenhouse food production in locations where greenhouses are currently not economically feasible.

9191-20, Session 6

Experimental study of direct transfer of concentrated solar radiation through optical fibres to high temperature thermal applications

Maryam Rahou, John Andrews, Gary Rosengarten, RMIT Univ. (Australia)

Employing optical fibres for transferring concentrated radiation from solar concentrators has potential advantages in terms of transmission energy efficiency, technical feasibility and cost-effectiveness compared to a conventional heat transfer system employing heat exchangers and a heat transfer fluid. The basic investigated system comprised a solar concentrator, secondary reflector, and optical fibres as the carrier of energy to the receiver. The relationship between transmission and length of fibre is studied experimentally for a selection of individual polymer clad fibres. A broadband light source with similar spectrum to the Sun is employed. The effects on transmission of varying the numerical aperture, hydroxyl content, and the core size of the fibres, as well as the angular distribution of the incident light, are investigated. The experimental results are compared with simulations using the ray tracing model, LightTools®. The initial results indicate that the best-performing fibres are capable of transmitting relatively high levels of solar energy over lengths up to 100 m with less loss compared to conventional methods.

9191-21, Session 6

Solar optical codes evaluation for modeling and analyzing complex solar receiver geometries

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Solar optical modeling tools are valuable for modeling and predicting the performance of solar technology systems. Four optical modeling tools were evaluated using the National Solar Thermal Test Facility heliostat field combined with non-conventional power tower receiver geometries as a benchmark. The four optical modeling tools evaluated were DELSOL, HELIOS, SolTrace, and Tonatiuh. All are available for free from their respective developers. DELSOL and HELIOS both use a convolution of the sunshape and optical errors for rapid calculation of flux profiles on the receiver surfaces. SolTrace and Tonatiuh use ray-tracing methods to determine reflected solar rays on the receiver surfaces and construct flux profiles. We found the ray-tracing tools, although slower in computation speed, to be more flexible for modeling complex receiver geometries, whereas DELSOL and HELIOS were limited to standard receiver geometries. We also list the strengths and deficiencies of the tools to show tool preference depending on the modeling and design needs.

9191-22, Session 6

Light redirecting system using sine-wave based panels for dense urban areas

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Cities and towns around the world are becoming more condensed due to the shrinking amount of buildable areas, which significantly reduces the amount of light that occupants have access to. This lack of natural lighting results in health, safety and quality of life degradation.

This paper presents a new technique of transmitting sunlight downward into narrow alleys and streets, by using a day-lighting guiding acrylic panel that is capable of changing the direction and distribution of the incident light. The core of the proposed daylight guidance system is made up of light transmission panels with high quality corrugations. The corrugations have sine wave shaped cross-section so that the panel functions as an optical diffuser perpendicular to the direction of sunlight propagation. The day lighting system consists of the corrugated panels and a lattice frame, which supports the panel. The proposed system is to be mounted on the building roof facing the sun so as to redirect the incident sunlight downward into the narrow alleys or streets. Since building sizes and orientations are different, the frame is arranged such that substantially deep light penetration and high luminance level can be achieved.

Simulation results show that the proposed panel improves the illuminance values by more than 200% and 400% in autumn and winter respectively, provides fan-out angle that exceeds 80° for certain solar altitudes and the transmitted power percentage varies from 20% to 90% as the solar altitude varies from 10° to 80°. Experimental results are in a good agreement with the simulations.

9191-23, Session PWed

LED lighting freeform lens for achieving octagon spot

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With a wealth of design freedom, freeform optical surface is gaining more and more uses in the field of LED lighting. In this paper, aiming at the commercial LED lighting application, a design method combining freeform surface and aspherical surface for reducing the source model error is presented, which can increase the accuracy of the light distribution effectively. Based on this method, a LED spotlight lens for realizing octagon spot is designed. By using the injection molding matchine, the plastic lens is manufactured, and it is tested by using a goniophotometer. The experimental result shows good consistence with the design. The method may be useful for improving the design precision in the LED lighting.

9192-37, Session PMon

High-quality UV: NIR thin film interference polarizers

Vladimir V. Novopashin, Alexsandr V. Shestakov, POLYUS Research and Development Institute (Russian Federation)

Interference polarizers can be successfully used in lasers and laser devices as independent optical element substituted crystal polarizers. Today, the use of crystal polarizers in some cases can lead to definite difficulties in accordance with peculiarities of laser cavity construction. The novel laser technologies and design of laser elements defined the new demands to optical coatings. In modern lasers interference polarizer can be considered as one of the main element that operates laser radiation. According to special optical outline and the requirements to optical characteristics of laser polarizers can be bryuster or mirror-type. The stable of spectral characteristic at a definite angle is one of the most important parameter. It was shown how optical thickness of each layer influence on angle stability. On the other hand high stable was achieved by using electron-beam ion assisted deposition. The coatings were deposited on the surface of optical glass BK-7 or quartz. Generally, refractory oxides were used. The achievement of the condensation layers structure was provided by active O2+ ions. It was shown, that smooth cleaning by neutral ions as before the evaporation definite separate layer, as after stabilized the optical properties of polarizer. Moreover, the using of ion source allowed increase laser damage threshold. It can be underline that some advantages of ion source revealed during evaporation materials in visible and especially ultra violet region. Also, laser strength was rather more at 1535 nm for ion-assisted deposited films. The average parameters were: transmission efficiency TP > 98%, extinction ratio PP/TS >500, laser damage more than 10 J/cm2, nanosecond pulse at 1064 nm.

9192-38, Session PMon

Investigation of diamond turning: of rapidly-solidified aluminum alloys

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In recent years, aluminum materials have been widely adopted for making optical mirror components in optical systems used within infrared spectral range. Aluminum 6061 is very often considered as the preferred optical material for making optical components for ground-based astronomy applications. One of the reasons for choosing this material is its high specific stiffness and good thermal properties. Also, historically, a lot of data has been gathered for this material. However, commercially available aluminum 6061 can be diamond turned to surface roughness values of approximately 5-8 nm. For the infrared spectral range this is adequate, but it cannot be used in the visual spectral range. In this study, we use a novel material made of rapidly solidified aluminum that is equivalent to the traditional 6061 alloy grade. The use of rapidly solidified aluminum may result in improved surface finish and better optical performance.

Rapid solidification process is realized using melt spinning operation, rendering the highest cooling rate of 106 K/s and as a result giving the finest microstructure. RSA 6061 properties are similar to tradition aluminum 6061, but its grain sizes are is very small. This paper first presents some backgrounds of rapidly solidified aluminum The paper also discuss the diamond turnability characteristics of both conventional aluminium and rapidly solidified aluminium will be discussed.

In this study, the surface roughness of RSA6061 and its grain structure have been evaluated using white light interferometers and scanning electron microscopy, respectively. Finally, some other indicators such as diamond tool wear, and optical performance are discussed in this research.

9192-39, Session PMon

Pyramid wavefront sensor for image quality evaluation of optical system

Dan Zhou, Li-xin Zheng, Shanghai Astronomical Observatory (China)

When the pyramid wavefront sensor is used to evaluate the imaging quality, placed at the focal plane of the aberrated optical system e.g., a telescope, it splits the light into four beams. Four images of the pupil are created on the detector and the detection signals of the pyramid wavefront sensor are calculated with these four intensity patterns, providing information on the derivatives of the aberrated wavefront. Based on the theory of the pyramid wavefront sensor, we are going to develop simulation software and a wavefront detector which can be used to test the imaging quality of the telescope. In our system, the subpupil image intensity through the pyramid sensor is calculated to obtain the aberration of wavefront where the piston, tilt, defocus, spherical, coma, astigmatism and other high level aberrations are separately represented by Zernike polynomials. The imaging quality of the optical system is then evaluated by the subsequent wavefront reconstruction. The performance of our system is to be checked by comparing with the measurements carried out using Puntino wavefront instrument (the method of SH wavefront sensor). Within this framework, the measurement precision of pyramid sensor will be discussed as well through detailed experiments. In general, this project would be very helpful both in our understanding of the principle of the wavefront reconstruction and its future technical applications. So far, we have produced the pyramid and established the laboratory setup of the image quality detecting system based on this wavefront sensor. Preliminary results are obtained, in that we have obtained the intensity images of the four pupils. Additional work is needed to analyze the characteristics of the pyramid wavefront sensor.

9192-40, Session PMon

Comparison of refractive dual-prism beam scanner used in near and far field

Anhu Li, Xinjian Gao, Ye Ding, Tongji Univ. (China)

Dual-prism scanner are a pairs of rotatable or tilting wedge prisms that can be used to continuously scan a laser beam over a specified angular range with a high resolution. When dual-prism scanner is used to track a remote object, the influence of thickness and distance of double prisms can be ignored. But for a near field tracking, the beam propagation path will generate a great tracking trajectory difference due to the structural influence. The paper makes a comparison of the beam scanning path performed by rotatable wedge prisms used in near and far field. According to my previous research achievements, the application of tilting orthogonal double prisms are discussed, which can steer the propagating beam to approach the tracking precision of submicron radian magnitude. The paper presents a forward solution and a reverse one for tilting orthogonal double prisms to track a known target point under an assumption that ignores the contributions made by the finite dimension of double prisms to ray tracing results. Considering the structural parameters of two prisms, the numerical solution of the double prism by seeking table method is proposed to solve the problem of tracking a target position in near field. Comparison results of that used in a near field and a far one validate the theoretical reasoning. This paper systematically concludes the theoretical model of rotatable and tilting double prism to perform the orientation and location tracking, which has an important application value in optical tracking and targeting direction.

9192-41, Session PMon

Differential measurement method for atmospheric refraction

Jian-jun Cao, Li-xin Zheng, Shanghai Astronomical Observatory (China)

Abstract: In traditional astronomical observation, it is seldom to observe objects with the altitude lower than 15 degree because of the effect of atmospheric refraction. But for the complete theoretical research of the atmospheric refraction, it is necessary to observe such objects, even with the altitude close to 0 degree. Also in the field of monitoring space targets, because the time of passing an observation site is short and the altitude is usually low, some objects at large zenith distance need to be observed. Taking the differential observation principle of Hipparcos astrometric satellite as reference, a new differential method is designed to measure atmospheric refraction: two reflection mirrors with fixed angle are installed in front of the incident light stop of a 20cm telescope, which make it possible to observe two sky regions at one time. First we can determine the practical angle by observing the two sky regions near the zenith, because the atmospheric refraction theoretical value is accurate enough at small zenith distances (e.g. zenith distance < 30 degree). Then the two regions of different altitudes at one azimuth are observed. The atmospheric refraction of low altitude can be calculated by combining the arc length from star catalog coordinates and the practical angle of the mirrors. The differential method is simple relatively and it can improve the ability of monitoring objects at large zenith distance with high precision. A schematic prototype of this kind of optical telescope has been developed and the preliminary experiment shows that the differential measurement for atmospheric refraction is feasible.

9192-42, Session PMon

Analysis of double conjugate zoom lens using tunable-focus lenses

Jiri Novak, Pavel Novak, Antonin Miks, Czech Technical Univ. in Prague (Czech Republic)

Various active optical elements, which enable a continuous change of their focal length, have been developed and analyzed in recent years that make possible to design absolutely novel optical systems, which have no analogy in classical optical system design. The main advantage of such novel optical systems is simpler mechanical design due to the fact that position of individual elements can be fixed and the change of optical parameters of the whole optical system is ensured by the tunability of focal length of individual elements. At present some commercially produced fluidic lenses with a variable focal length are available. However, their parameters are not still ideal and it is likely that various superior types of tunable-focus lenses will appear in next years, from which various novel optical systems will be possible to design. The aim of this work is to analyze imaging parameters of an optical system with variable magnification or focal length, which keeps the position of object and image planes and entrance and exit pupil planes fixed and does not move its elements during the change of the magnification or focal length (double conjugate zoom lens system). This effect can be achieved using tunable-focus lenses. The double conjugate zoom lens with tunable focus lenses satisfies the requirement that object, image and pupil planes are fixed during the change of magnification or focal length. Because of three conditions must be fulfilled the double conjugate zoom lens system from tunable focus lenses must be composed of at minimum three optical elements as the distances between individual elements must hold fixed with the magnification or focal length change. Formulas are derived, which enable to determine focal lengths of individual elements of the optical system in a general case, when an object is situated in a finite or infinite distance from the optical system. Such an optical system can be principally used in the design of riflescopes with a variable magnification. This design of the riflescope has the advantage of the fixed position of optical components with tunable focal lens and the position of the exit pupil does not change and stays fixed in a fixed distance from the eyepiece during the change of magnification.

9192-43, Session PMon

Research on properties of an infrared imaging diffractive element

Martyna Rachon, Karolina Wegrzynska, Marta Doch, Karol Kakarenko, Agnieszka Siemion, Jaroslaw Suszek, Maciej Sypek, Andrzej Kolodziejczyk, Warsaw Univ. of Technology (Poland)

Novel thermovision imaging systems having high efficiency require very sophisticated optical components. This paper describes the diffractive optical elements which are designed for the wavelengths between 7 and 14 ?m for the application in the FLIR camera. In the current paper authors present phase only diffractive elements manufactured in the etched gallium arsenide. Due to the simplicity of the production process only binary phase elements were designed and manufactured. Such solution exhibits huge chromatic aberration. Moreover, performance of such elements is rather poor, which is caused by two factors. The first one is the limited diffraction efficiency (c.a. 40%) of the binary phase structures. The second problem lies in the Fresnel losses on the two surfaces (50%). Mentioned structures are not useful for direct imaging purposes but are sufficient for point spread function (PSF) measurements, which is the main aim of this work.

Different diffractive elements were compered. The first one was the equivalent of the lens designed on the basis of the paraxial approximation. For the second designing process non-paraxial approach was used. It was due to F#=1. For non-paraxial design the focal spot is smaller and better focused. Unfortunately, both binary structures suffer from big chromatic aberrations.

9192-44, Session PMon

Near-infrared imaging equipment that detects small organic substances in thick foods

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Contamination of foods by foreign substances is a serious problem because it often affects human health. However, detection of small organic substances in foods is difficult with conventional metal detectors and X-ray detection apparatus. Near-infrared imaging techniques enable the detection of these substances in real time, but the detectable thickness of the foods is less than 1 mm because of strong scattering inside them. In this work, we develop near-infrared imaging equipment that detects foreign substances in foods thicker than 1 mm. A laser diode with lasing wavelength of 808 nm and maximum output of 75 W was used as the light source. The output laser beam was converted into parallel light using a telecentric lens and irradiated on the samples. The irradiated light power distribution was highly uniform, with a circular area 20 mm in diameter. Another telecentric lens was set in front of a CMOS camera to lead only parallel transmitted light to the camera while cutting out the scattered light. We eliminated low spatial frequency components from the images to emphasize the image boundary and increase the contrast between the substances and the foods. We observed transmission images of a 0.3-mm-diameter wooden stick on which sliced hams with various thicknesses are placed. The stick is distinguished until 2-mm-thick sliced hams are used. We also distinguished 0.5 mm-diameter bones in fish and 5 mm-diameter bones in wing sticks. The thicknesses of the fish and the wing sticks are 30 mm and 20 mm, respectively.

9192-45, Session PMon

Analyzing of light pattern uniformity in multi-chips LED lighting

Yu-Hsuan Chen, Chi-Hung Lee, Jou-Hui Lin, Shih-Hsin Ma, Feng Chia Univ. (Taiwan)

Multiple chips are often bonded in a small single package of LED to obtain higher light flux output. However, the non-uniformity of light pattern always exists due to the high order collimating lamp, which uses the MCLED (Multi-chips LED) as the source. In this paper, the light pattern uniformity of lamp composed of four-in-one MCLED, whose thickness of phosphor layer and the distance between the lamp and the screen are respectively 1 mm and 10 mm, is simulated and analyzed. The ray tracing simulated by computer with varying the spacing of chips, concentration of phosphor, shape of lamp, and the corresponding uniformity of light pattern will be analyzed and discussed in detail.

9192-47, Session PMon

Study of CCT varying by volume scattering diffuser with moving and rotating white light LED

Shih-Hsin Ma, Wen-Chao Huang, Yu-Hsuan Chen, Jou-Hui Lin, Feng Chia Univ. (Taiwan)

In this study, the corrected color temperature (CCT) of white light, which originates from a white light LED (WLED) and passes through a volume-scattering diffuser (VSD), is investigated. The VSD with thickness of 2mm is fabricated by mixing the 2um-sized PMMA scattering particles and the epoxy glue with different concentration values. Moreover, in order to understand the influences of the illuminated area and the scattering path of VSD on CCT values, the bullet-headed and lambertian-type WLEDs are assembled for different positions and distinct orientations along the optical axis in a black cavity. A detailed comparison between results regarding the white light with and without passing through the VSD is offered. The results of this research will help to improve the colorful consistency of the white light LED lamps which use diffusers.

9192-48, Session PMon

LED collimation module for time sequential back-light system

Jou-Hui Lin, Chi-Hung Lee, An-Ching Tai, Yu-Hsuan Chen, Shih-Hsin Ma, Feng Chia Univ. (Taiwan)

In this study, a collimated LED light source has been developed as a colorful liquid crystal display backlight, which is driven by a two-field driving scheme to display color. In each field, the angular rays of two colors from LEDs are collimated by a collimation lens, redirected by a light guide and converged by a cylindrical-lens array to map into corresponding sub-pixel positions for efficiently displaying color image. The simulation results of the backlight module and the corresponding experimental results will be discussed in detail.

9192-49, Session PMon

Manufacturing of freeform mirror by milling and altering its optical characteristics by ns-laser polishing and ALD coatings

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In this study we investigated a method for polishing and coating machined freeform mirrors suitable for UV-VIS applications, with emphasis on developing processes that are also cost effective. The tested parts were two types of miniature aluminium freeform mirrors used as part of a compact multipoint fiber optic probe that can be used in spectral measurements for online process monitoring. The parts were designed by combining optical modelling with the mechanical structure. Both ultra precision diamond tooling and CNC machining were used in the milling of the freeform mirrors to test how well the nanosecond (ns) -laser polishing and the atomic layer deposition (ALD) improve the surface properties of the mirrors. Two types of ALD coatings, aluminium oxide and silicon dioxide were tested. The surface roughnesses of mirrors were analyzed by optical profiler after ns-laser polishing and prior to coating them on a Beneq TFS 200 ALD device. The measured surface roughness Ra value of uncoated aluminium mirrors varied between 2.5 to 190 nm and after the processing in the best case the surface roughness was half of the surface roughness of the original unprocessed mirror.

For the testing of the spectral properties all the mirrors were coupled to a multipoint fiber-optic UV-VIS spectrometric test setup for spectral measurements. The results show that improvement in the surface roughness can be seen with ns-laser polished and ALD coated aluminium surfaces and that coatings affect the mirror reflectance characteristics.

9192-50, Session PMon

Portable system to luminaries characterization

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For illumination designers is important to know the illumination distribution and the type of sources. They can use several viewers of IES files or trust in the characterizations provided by the producers of luminaries. Unfortunately, nor all illumination sources have their corresponding data sheets.

The complete portable system for luminaries’ characterization is formed by:

• Irradiance profile meter, which can generate photometries of luminaries of types B and C formats. The last type covers indoor illumination requirements and luminaries for general areas, while type B refers to luminaries for floodlighting. This meter has several advantages such as: the size, weight, etc. And additional attribute is given by the color sensor implemented, which allows to know the color temperature of luminary under analysis.

• Graphic Interface Unit (GUI) can control the meter, acquire the data obtained by the sensor and graph them in 2D, under Cartesian and polar formats, in several languages. The graph can be exported in several formats. Data can be imported or exported to IES files, in accordance with IES LM-63-2002 or LM-63-1995. The first and last attribute make this GUI a complete tool. These remarkable characteristics differentiate this GUI. The IES files are necessary not only know the distribution of illumination, but also to plain the construction of buildings by means of specialized softwares, such as Autodesk Revit.

This proposal can be considered as a viable option for enterprises of illumination designers, due to the relatively low investment level and considering the complete illumination characterization provided.

9192-51, Session PMon

Phase retrieval of microscope objects using the Wavelet-Gabor transform method from holographic filters

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The Gabor Wavelet Transform (GWT) is used as a method of reconstruction of holograms from holographic filters. The GWT offers certain special characteristics over other reconstruction methods. GWT allows dynamic and automate analysis of the system and it is not required to perform a spatial filtering. At the same time GWT gives us the possibility to obtain the heights of objects and spatial dimensions, this task according to the change of the samples over short periods of time. In this work, different experimental setups for obtaining holographic filters from objects with microscopic dimensions are presented. In the same way, we implemented an algorithm based on GWT as a method of reconstruction of holographic filters in order to obtain the phase information and amplitude of the object. In this paper, the reconstruction of different object holograms are shown and the GWT algorithm is compared with the classical method of the Fresnel Diffraction Integral through the S-FFT. To validate the functionality and effectiveness of the procedure, it will be measure the computational time and quality of information retrieved.

9192-52, Session PMon

Controllable focal spot for direct-drive laser fusion based on electro-optic effect

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In direct-drive laser fusion, the sufficient uniformity of focal spot to produce high compression and central ignition is required. However the laser beams could not be made sufficient uniform to compress the shell symmetrically inward. We proposed a novel scheme to achieve controllable focal length based on electro-optic effect. The electro-optic crystal is set in the front and added with similar spherical electro field. Hence the wavefront of laser beam is transformed propagated through the electro-optic crystal. The focal spot of the transformed laser beam would be changed on the target. Theoretical analysis and numerical simulation has been made, and the scheme was the optimized further. The results show that the scheme could achieve enough controllable focal spot on the target.

9192-53, Session PMon

Research on chromatic properties of high-order kinoform

Karolina Wegrzynska, Martyna Rachon, Marta Doch, Agnieszka Siemion, Jaros?aw Suszek, Maciej Sypek, Andrzej Kolodziejczyk, Warsaw Univ. of Technology (Poland)

This work is dedicated to the evaluation of the chromatic properties of the high order kinoforms. Typical kinoform (of the first order) is a phase only structure having the phase retardation varying in the range 0-2π. Such structures are very commonly used in many practical applications for different ranges of electromagnetic radiation like ultraviolet, visible, infrared, terahertz and millimeter waves. Besides those benefits such structures have one crucial disadvantage - they suffer from big chromatic aberration. This limits their practical application only to narrowband work, where main wavelength must be well defined (??/?<<1). This paper presents other type of diffractive structures called high order kinoforms (HOK). They exhibit phase retardation of n2π, where n is an integer number much bigger than 1. Due to this fact they are relatively thin and therefore can be manufactured using laser lithography in deep etched thick photoresist. On the other hand they are thick enough to suppress chromatic aberrations. In comparison to the well-known Fresnel lens, high order kinoform structure has precisely controlled phase retardation between different zones. In the case of For the Fresnel lens, phase retardations between different zones are random (designing process is based on the geometrical optics).

In the case of the high order kinoform spherical lens - taking into account the real size of the detector - it can be shown that the most of the energy in the focal spot will be registered for different wavelengths. The paper presents simple theoretical considerations, numerical modeling and their experimental evaluation.

9192-54, Session PMon

Optimized restoration of wavefront coded images

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Wavefront coding uses a special aspheric optics and digital image processing to extend the depth of focus in imaging systems. An intermediate blurred image is generated by the spatial convolution of the image with the point spread function (PSF) of a cubic phase mask. Restoration tests are performed on an optically encoded image. The image restoration given by a deconvolution procedure that involves the PSF of the imaging system is not always the best option. It is limited by the perfect PSF of an imaging system. We have performed numerical construction of the PSF from the optical parameters of the system. An optimization is achieved by fitting the low contrast experimental PSF of the system and the numerical PSF by means of a genetic algorithm in order to obtain the restored image. Results of the optimized restoration of wavefront coded images by means of genetic algorithms are shown.

9192-55, Session PMon

Controllable compliant manufacture technique for space off-axis aspheric optics

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As a special aspheric optics, the off-axis aspheric optics not only requires high surface form accuracy, but also the off-axis angle, the off-axis distance, the curvature of the vertex, the conic constant etc. These aspects make the off-axis aspheric much more difficult to fabricate. The traditional optical manufacture methods also exhibits uncontrollability including the machining tool wear, the aspheric misfit, and instability of the technology parameters, which also makes it much more difficult to satisfy the manufacture demands for the off-axis aspheric in the process. The tool in Magnetorheological Finishing (MRF) is a conformal “polishing tool” under high intensity magnetic. The “polishing tool” can conform to the curvature variant of the aspheric, the removal function can be modeled, and the machining process can be also controlled by computer. Therefore, MRF is a controllable compliant manufacture technique. The key techniques applied in the off-axis aspheric optics including the surface form error model, removal function model and compensation in aspheric, and the form accuracy generation with 4-dimension (1-dimension time and 3-dimension space) control. Furthermore, an off-axis aspheric is used as an example to validate the effectiveness and advantage of controllable compliant manufacture technique. Its final surface form error is improved to 0.014?(?=632.8nm), which provides new ways for the high-efficiency and high-accuracy manufacture of the off-axis aspheric optics.

9192-56, Session PMon

Mold production for polymer optics

Marco Speich, Rainer Börret, Jonas Raab, Hochschule Aalen (Germany)

The fields of application for polymer optics are huge and thus the need for polymer optics is steadily growing. Most polymer optics are produced in high numbers by injection molding. Molds and dies have to fulfill special requirements to produce good optical parts. Polishing is usually the last step in the common process chain for the production of molds for polymer optics. Usually this process step is done manually by experienced polishers. Due to the small number of skilled professionals and a risk of health problems because of the monotonous work the idea was to support or probably supersede manual polishing.

Polishing by using an industrial robot as movement system enables totally new possibilities in automated polishing. This work focuses on the surface generation with a newly designed polishing setup and on the code generation for the robot movement. The process starts on ground surfaces. With different tools and polishing agents surfaces that fulfill the requirements for injection molding of optics can be achieved. To achieve this the attention has to be focused not only on the process itself but also on tool path generation. A proprietary software developed in the Centre for Optical Technologies in Aalen University allows the tool path generation on almost any surface. This allows the usage of the newly developed polishing processes on different surfaces and enables an easy adaption. Details of process and software development will be presented as well as results from different polishing tests on different surfaces.

9192-59, Session PMon

Effect of injection molding processing conditions on optical properties of polyetherimide

Wei Zhao, Christopher Wall, Raghavendra Maddikeri, Andy May, SABIC Innovative Plastics (United States)

SABIC's ULTEM(TM) (polyetherimide) resin has been the choice of material for injection moldable micro lenses and lens arrays in optical communication components such as transceivers due to its unique combination of physical, thermal and optical properties including high refractive index, low absorption in near IR range, good dimensional stability and high heat performance.

It's known that processing conditions affect properties of final parts. Often, the processing conditions are optimized for best mechanical properties, and their effect on optical properties is sidelined. In this study, effect of injection molding processing conditions on optical properties of polyetherimide resin is discussed. Various processing conditions such as different melt temperatures, residence times and injection speeds were used to mold polyetherimide samples. And samples' optical properties such as yellow index, haze, optical transmittance, refractive index and birefringence were determined. Best injection molding processing conditions were identified for polyetherimide resin used in optical applications.

9192-1, Session 1

The role of aberration analysis in modern optical design with a focus on zoom lenses *(Invited Paper)*

Julie L. Bentley, Univ. of Rochester (United States)

Before the use of modern ray tracing programs, aberration theory was an essential tool in the design of optical systems. However, the field of optical design has changed considerably in the past few decades. For example, with global optimization algorithms one can often find many solutions to a single problem quickly. As a result, aberrations are sometimes ignored by new designers and the ability to determine the limiting aberrations through transverse ray aberration plots may be in danger of becoming a lost art. But aberration theory and aberration analysis still have a role to play in modern optical design. They can provide insight into design limitations, tolerance sensitivity, and the manufacturability of the underlying design form. This becomes extremely useful when searching for cost-effective solutions. This talk will focus on modern zoom lens design and the use of aberrations to guide the understanding of the design limitations of several different example systems.

9192-2, Session 1

Using saddle points for challenging optical design tasks

Irina L. Livshits, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Zhe Hou, Technische Univ. Delft (Netherlands); Pascal van Grol, TNO (Netherlands); Yifeng Shao, Technische Univ. Delft (Netherlands); Maarten van Turnhout, TNO Science and Industry (Netherlands); H. Paul Urbach, Florian Bociort, Technische Univ. Delft (Netherlands)

In typical optical design tasks, the presence of many local minima in the optical merit function landscape makes design non-trivial. With the method of Saddle Point Construction (SPC) which was developed recently ([F. Bociort and M. van Turnhout, Opt. Engineering 48, 063001 (2009)]) new local minima are obtained efficiently from known ones by adding and removing lenses in a structured way. We will present recent results in our attempt to make SPC a robust practical tool.

In this paper the emphasis is on the design of wide-angle pinhole lenses, which pose significant design challenges. As objectives in covert observation cameras this type of lenses are useful for security purposes. For this kind of designs, our experience shows that the design process with traditional methods and standard software tools is easily trapped in sub-optimal local minima.

We will present designs of wide-angle pinhole lenses where, after using traditional design methods, by applying SPC we were able to further improve the designs. Switching rapidly from one minimum to another one gave us the possibility to choose the most promising of them. It was even possible to improve performance while using one lens less than in previous design stages. The examples also show that SPC can be easily integrated with traditional design methods.

For a better understanding of SPC, examples will also be given that show how to visualize the saddle point that can be constructed at any surface of any imaging system.

9192-3, Session 1

Double surface imaging designs with unconstrained object to image mapping under rotational symmetry

Jiayao Liu, Juan Carlos Miñano, Pablo Benítez, Univ. Politécnica de Madrid (Spain)

In this work, a novel imaging design formed by two optical surfaces with rotational symmetric is presented. In these designs, both object and image shapes are given but mapping from object to image is obtained as a result of the design. In the examples considered, the image from a planar object surface is virtual and located at infinity and is seen from known pupil, which can emulate a human eye.

The differential equation method is used to provide single optical surface imaging designs by considering the local properties of the surfaces and the wave fronts. In the first introductory part, both the rotational symmetrical and the freeform single surface imaging designs are

presented using the differential equation method. In these designs, not only the mapping is obtained in the design process, but also the shape of the object is found.

In the second part, the method is extended to two surfaces designs with rotational symmetry and the astigmatism of the image has been studied. By adding one more optical surface to the system, the shape of the rotational symmetrical object can be designed while controlling the tangential rays and sagittal rays simultaneously. As a result, designs without astigmatism (at the small pupil limit) on a planar object surface have been obtained.

9192-4, Session 1

Exact space aberrations' distribution in centered optical systems

Boian A. Hristov, Central Lab. of Optical Storage and Processing of Information (Bulgaria)

This paper demonstrates exact real distribution of field aberrations in object and image space of optical systems obtained with the help of the Exact Theory of Aberrations. We start with the formulation of the conditions, which ensure the existence of object surfaces with corrected aberrations. Then we develop specific algorithms to calculate the exact coordinates of the object surfaces and the conjugated image surfaces. The same algorithms allow us to determine the horizontal and the vertical asymptotes of the functions for space distribution of the aberrations, as well as their maximums or minimums.

Identified are the real correctional abilities of a single spherical surface, of a single optical element and of a group of optical elements.

Based on this research a method for design of optical systems is developed.

Examples are given for a typical space aberration's distribution of a single surface, of a single optical element or of a group of optical elements. Examples of optical systems designed with our method are demonstrated.

9192-5, Session 1

Design and analysis of an adaptive lens that mimics the performance of the crystalline lens in the human eye

Agustín Santiago-Alvarado, Angel S. Cruz-Félix, Fernando Iturbide-Jiménez , María de Jesús Martínez-López, Magaly Ramírez-Como, Ingrid R. Vásquez-Báez, Victor D. Armengol-Cruz, Univ. Tecnológica de la Mixteca (Mexico)

Tunable lenses are optical systems that have attracted much attention due to their potential applications in such areas like ophthalmology, machine vision, microscopy and laser processing. In recent years we have been working in the analysis and performance of a liquid-filled variable focal length lens, this is a lens that can modify its focal length by changing the amount of water within it. Nowadays we extend our study to a particular adaptive lens known as solid elastic lens (SEL) that it is formed by a main elastic body made of polydimethylsiloxane (PDMS Sylgard 184). In this work we present the design, simulation and analysis of an adaptive solid elastic lens that in principle imitates the accommodation process of the crystalline lens in the human eye. For this work we have adopted the schematic eye model developed in 1985 by Navarro et al.; this model represents the anatomy of the eye as close as possible to reality by predicting an acceptable and accurate quantity of spherical and chromatic aberrations without any shape fitting. An opto-mechanical analysis of the accommodation process of the adaptive lens is presented, by simulating a certain amount of pressure applied onto the SEL using the finite element method with the commercial software SolidWorks®. We also present ray-trace diagrams of the simulated compression process of the adaptive lens using the commercial software OSLO®.

9192-6, Session 2

Caustic surfaces of a plane wavefront refracted by a smooth arbitrary surface

Maximino M. Avendaño-Alejo, Univ. Nacional Autónoma de México (Mexico)

We study the formation of caustic produced by smooth arbitrary surfaces considering a plane wavefront propagating parallel to the optical axis and impinging on the refracting surface. The caustic can be defined as the envelope for refracted rays crossing an optical system. We have already seen that the shape of the caustic surface can represent the monochromatic aberrations that we call image errors, furthermore the shape of the caustic can be modified by changing the parameters of the lens in such a way that if the caustic surfaces is vanished the optical system produces a perfect image, on the other hand for a caustic possessing a large area it could be applied to design no-imaging optical systems. The shape of the caustic depends only on the indices of refraction involved in the process of refraction, the arbitrary surface and its first and second derivatives. We provide an analytic equation for the caustic surface after refraction of a plane wave from any rotationally symmetric surface. This formula is applied to evaluating and comparing the caustic surfaces formed by smooth arbitrary plano-convex lens immersed in an isotropic with possible potential applications in the microscopy field. Finally, we provide the condition for rays that undergo total internal reflection.

9192-7, Session 2

Research on the controlling thermal defocus aberration for the infrared imaging system based on wavefront coding

Di Chen, Liquan Dong, Yuejin Zhao, Xiaohua Liu, Cuiling Li, Xiaohu Guo, Zhu Zhao, Yijian Wu, Beijing Institute of Technology (China)

We describe the application of the wavefront coding technique for infrared imaging system to control thermal defocus. For traditional infrared imaging system, athermalization and achromatization are necessary to maintain imaging performance which may increase complexity and cost of the imaging system. Wavefront coding includes a phase mask at the pupil which can re-modulate the wave front so as to produce an encoded image. After digital processing, the system is insensitive to defocus. In this paper, the combination of wavefront coding technique and infrared imaging system has been discussed. We report here the optic design of a wavefront coding infrared imaging system based on ZEMAX. The phase mask is designed by ZPL macros, and the operands are written to optimize the modulation transfer function in the range of working temperature. What's more, for comparison, we designed another two traditional infrared imaging systems, one with traditional athermalization method, and the other one without athermalization method. The latter one is the same as the system based on wavefront coding except for the insertion of phase mask. The simulation results show that the infrared imaging system based on wavefront coding can accept good imaging performance in a temperature varying from -60ºC to 60ºC, at the same time the weight and cost of optical elements are reduced by approximately 40%.

9192-8, Session 2

Complex imaging with ray-rotating windows

Aidan Strathearn, James Moncreiff, Stephen Oxburgh, Johannes Courtial, Univ. of Glasgow (United Kingdom)

We study the imaging properties of windows that rotate the direction of transmitted light rays by a fixed angle around the window normal [A. C. Hamilton et al., J. Opt. A: Pure Appl. Opt. 11, 085705 (2009)]. We

previously found that such windows image between object and image positions with suitably defined complex longitudinal coordinates [J. Courtial et al., Opt. Lett. 37, 701 (2012)].

Here we extend this work to object and image positions in which any coordinate can be complex. This is possible by generalising our definition of what it means for a light ray to pass through a complex position: the vector from the real part of the position to the point on the ray that is closest to that real part of the position must equal the cross product of the imaginary part of the image position and the normalised light-ray-direction vector. In the paraxial limit, we derive the equivalent of the lens equation for planar and spherical ray-rotating windows.

These results allow us to describe complex imaging in more general situations, involving combinations of lenses and inclined ray-rotating windows. We illustrate our results with ray-tracing simulations.

9192-9, Session 2

Study of camera calibration process with ray tracing

Anne-Sophie Poulin-Girard, Xavier Dallaire, Audrey Veillette, Simon Thibault, Denis Laurendeau, Univ. Laval (Canada)

Camera calibration is essential for any optical system used to obtain 3D measurements from images. The precision of the 3D depth estimation relies on an appropriate camera model and the accurate determination of model parameters. Those parameters are sensitive to environmental conditions and it is well established that a vision system should be calibrated in operating conditions. This is not always possible since the calibration process is often tedious and time-consuming. Unfortunately, the use of wrong calibration parameters for 3D reconstruction and measurements leads to low performance of the system and inaccurate depth estimation. This paper presents a technique using an existing camera model and an optical design software to perform calibration simulations. This virtual calibration technique allows for a study of the impact of environmental conditions on the calibration parameters. Using this procedure, it is also possible to predict the statistical behavior of the calibration parameters considering the chosen fabrication processes and tolerances. It can assist vision scientists in the choice of the optical system that answers best the requested precision of the 3D reconstruction. This technique could eventually be integrated in the lens design process to create more reliable optical systems that could be calibrated and used in a range of environmental conditions with a very small variation of their calibration parameters.

9192-10, Session 3

Diffraction limited integral field spectrographs for large telescopes *(Invited Paper)*

James E. Larkin, Univ. of California, Los Angeles (United States)

As telescopes become larger and adaptive optics systems become more capable, integral field spectrographs offer a range of advantages over traditional cameras and spectrographs. I'll discuss the design choices in the spectrograph for the Gemini Planet Imager (GPI) and the design of the IRIS instrument for the Thirty Meter Telescope. Both spectrographs are fully cryogenic with minimal wavefront error, high throughput and relatively large fields of view. I'll also describe how speckles are spectrally suppressed in the GPI instrument in order to gain another factor of 10 in contrast between planets and their host stars

9192-11, Session 3

Conception of a cheap infrared camera using a Fresnel lens

Tatiana Grulois, Guillaume Druart, Nicolas Guérineau, ONERA (France); Arnaud Crastes, ULIS (France); Hervé Sauer, Pierre Chavel, Laboratoire Charles Fabry, Institut d'Optique, CNRS (France)

Huge efforts are being made to design innovative imagers in both cooled and uncooled infrared.

In the cooled infrared, the target is to develop a camera that is compact, light and able to quickly cool down. A few years ago, a first step in the miniaturization process was done by integrating a lens inside the dewar that used to be a sealed environment reserved for the packaging and the cooling of the detector. However, the weight and the cooling time of the camera have necessarily been increased because of the mass of the cold lens added. That's why we propose now to go further by giving an imagery property to the dewar without integrating a single optics. To reach this design approach, our goal is to give an optical function to the window, the cold diaphragm or the cold filter existing inside the dewar. Since these elements are thin optical plates, we are working on the opportunity to use planar optics such as Fresnel lenses, microlens arrays and diffraction gratings.

In the uncooled infrared many industrials are currently interested in designing very cheap cameras for low-cost applications. Acknowledging that infrared optical elements are generally made with expensive materials like germanium, the challenge is to explore new designs using cheap materials such as silicon, chalcogenide glasses or polyethylene. The use of planar optics could eliminate the problems of absorption that occurs with silicon and polyethylene in the LWIR.

In this presentation we will present some of the architectures we have developed about these issues.

9192-12, Session 3

Multi-aperture microoptical system for close-up imaging

René Berlich, Andreas Brückner, Robert Leitel, Alexander Oberdörster, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Mathias Schulz, Rainer Fischer, Andreas Lindner, Sypro Optics GmbH (Germany); Frank C. Wippermann, Andreas Bräuer, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Modern applications in biomedical imaging, machine vision and security engineering require close-up optical systems with high resolution. Combined with the need for miniaturization and fast image acquisition of extended object fields, the design and fabrication of respective devices is extremely challenging. Standard commercial imaging solutions rely on bulky setups or depend on scanning techniques in order to meet the stringent requirements. Recently, our group has proposed a novel, multi-aperture approach based on parallel image transfer in order to overcome these constraints. It exploits state of the art microoptical manufacturing techniques on wafer level in order to create a compact, cost- effective system with a large field of view. However, initial prototypes have so far been subject to various limitations regarding their manufacturing, reliability and applicability.

In this work, we demonstrate the optical design and fabrication of an advanced system which overcomes these restrictions. In particular, a revised optical design facilitates a more efficient and economical fabrication process and inherently improves system reliability.
An additional customized front side illumination module provides homogeneous white light illumination over the entire field of view while maintaining a high degree of compactness. Moreover, the complete imaging assembly is mounted on a positioning system. In combination with an extended working range, this allows for adjustment of the system's focus location. The final optical design is capable of capturing an object field of 36x24 mm^2 with a resolution of 150 lp/mm. Finally, we present experimental results of the respective prototype that demonstrate its enhanced capabilities.

9192-13, Session 3

Optical performance analysis of plenoptic camera systems

Christin Langguth, Alexander Oberdörster, Andreas Brückner, Frank C. Wippermann, Andreas Bräuer, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

In the past decade the demand for 3D image acquisition systems and processing techniques significantly increased, due to modern applications in machine vision and consumer electronics. Despite of considerable advances, capturing 3D object information has always been an essential limitation in conventional photography. The two-dimensional sensor integrates the intensity of all light rays per pixel that are incident on the camera aperture from the three-dimensional object space. Hence, the angular information regarding how light has propagated through the main lens is lost.

Adding an array of microlenses in front of the sensor transforms the capabilities of a conventional camera to capture both spatial and angular information within a single shot. This plenoptic camera is capable of obtaining depth information and providing it for a multitude of applications, e.g. artificial re-focusing of photographs. Without the need of active illumination it represents a compact and fast optical 3D acquisition technique with reduced effort in system alignment. Since the extension of the aperture limits the range of detected angles, the observed parallax is reduced compared to common stereo-systems, which results in a decreased depth resolution. Besides, the gain of angular information implies a degraded spatial resolution. This trade-off requires a careful choice of the optical system parameters.

We present a comprehensive assessment of possible degrees of freedom in the design of plenoptic systems. Utilizing a custom-built simulation tool, the optical performance is quantified with respect to particular starting conditions. Furthermore, a plenoptic camera prototype is demonstrated in order to verify the predicted optical characteristics.

9192-14, Session 3

Proof-of-concept demonstration of a miniaturized multi-resolution refocusing imaging system using an electrically tunable lens

Lien Smeesters, Gebirie Y. Belay, Heidi Ottevaere, Youri Meuret, Michael Vervaeke, Jürgen Van Erps, Hugo Thienpont, Vrije Univ. Brussel (Belgium)

Refocusing multi-channel imaging systems are nowadays only commercially available in bulky and expensive designs. Compact wafer-level multi-channel imaging systems have until now only been published without refocusing mechanisms, since classical refocusing concepts cannot be integrated in a miniaturised configuration. This lack of refocusing capabilities limits the depth-of-field of these imaging systems and therefore their application in practical systems. We designed and characterised a wafer-level two-channel multi-resolution refocusing imaging system, based on a voltage electrically tunable liquid lens and a design that can be realized with wafer-level mass-manufacturing techniques. One wide field-of-view channel (2x40°) gives a general image of the surrounding with a low angular resolution (0.078°), whereas the high angular resolution channel (0.0098°) gives a detailed image of a small region of interest with a much narrower field-of-view (2x7.57°). The latter high resolution imaging channel contains the tunable lens and therefore the refocusing capability. The performances of this high resolution imaging channel were experimentally characterised in a proof-of-concept demonstrator. The experimental and simulated depth-of-field and resolving power correspond well. Moreover, we are able to obtain a depth-of-field from 0.25m until infinity, which is a significant improvement of the current state-of-the-art static multi-channel imaging systems, which show a depth-of-field from 9m until infinity. Both the high resolution and wide field-of-view imaging channels show a diffraction-limited image quality. The designed wafer-level two-channel imaging system can form the basis of an advanced three-dimensional stacked image sensor, where different image processing algorithms can be simultaneously applied to the different images on the image sensor.

9192-15, Session 3

Consumer electronic optics: how small can a lens be?

Simon Thibault, Univ. Laval (Canada); Hu Zhang, Jocelyn Parent, Patrice Roulet, ImmerVision (Canada)

In 2014, miniature camera modules are applied to a variety of applications such as webcam, mobile phone, automotive, endoscope, tablets, portable computers and many other products. Mobile phone cameras are probably one of the most challenging parts due to the need for smaller and smaller total track length (TTL) and optimized embedded image processing algorithms. As the technology is developing, higher resolution and higher image quality, new capabilities are required to fulfil the market needs. Consequently, the lens system becomes more complex and requires more optical elements and/or new optical elements. What is the limit? How small an injection molded lens can be? We will discuss those questions by comparing two wide angle lenses for consumer electronic market. The first lens is a 6.5mm (TTL) panoramic (180 deg FOV) lens built in 2012. The second is a more recent (2014) panoramic lens (180 deg FOV) with a TTL of 3.8mm for mobile phone camera. Both optics are panomorph lenses used with megapixel sensors. Between 2012 and 2014, the development in design and plastic injection molding allowed a reduction of the TTL by more than 40%. This TTL reduction has been achieved by pushing the lens design to the extreme (edge/ central air and material thicknesses as well as lens shape). This was also possible due to a better control of the injection molding process and material (low birefringence, haze and thermal stability). These aspects will be presented and discussed. During the next few years, we don't know if new material will come or new process but we will still need innovative people and industries to push again the limits.

9192-16, Session 4

Overview of diffraction gratings technologies for space-flight satellites and in astronomy

Arnaud Cotel, HORIBA Jobin Yvon S.A.S. (France)

The diffraction gratings are widely use in Space-flight satellites for spectrograph instrument or in Ground-based Telescope in Astronomy. The diffraction gratings are one of the key optical components of such system and have to exhibit very high optical performances.

HORIBA Scientific company with Jobin Yvon Grating Technology is in the forefront of such gratings development.

During the past decade, HORIBA Scientific has developed a unique expertise in diffraction grating design and manufacturing processes for holographic, ruled or etched gratings.

We will present in this conference an overview of diffraction grating technologies designed for space and astronomy applications. We will firstly review new developments of transmission Fused Silica Etched (FSE) grating type uses in the UV and NIR spectral range for high-efficiency purpose and low polarization dependence, compatible with cryogenic environment in ground-based telescopes and possibly used in a grism or immersed grating configuration.

Then, an overview of a ruled grating recent project will be shown where a set of 30gr/mm groove density gratings, plane shape with a shallow blazed angle optimized from 2 to 5µm have been successfully manufactured. These gratings have been space qualified with extensive environmental tests and characterized to be installed in a spectrograph. The goal is to obtain a high resolution image of a planet atmosphere and to retrieve its spectral properties.

Finally, we will report on results of holographic, high groove density gratings produced for NUV and FUV spectral range, such as the NASA's Interface Region Imaging Spectrograph (IRIS) diffraction gratings.

9192-17, Session 4

Chromatic error correction of diffractive optical elements at minimum etch depths

Jochen Barth, Tobias Gühne, Airbus Defence and Space (Germany)

The integration of a diffractive optical element (DOE) into an optical design opens up interesting new possibilities for applications in sensing and illumination. If the resulting optics shall be used in a larger spectral range we must correct not only the chromatic error of the conventional, refractive, part of the design but also of the DOE. DOEs contain a pixilated surface structure etched into the optical material which introduces phase lags between waves transmitted through the DOE along different paths. Because the phase lag results as a measure of the glass thickness in units of the wavelength it is a linear function of the wavelength of the transmitted light. This results in a chromatic error larger than for refractive optics which can be compensated in a similar way by combining two DOEs of different glasses, and requires an increased etch depth for the surface structure of the two DOEs which hampers the manufacturing of such DOEs with satisfactory performance. Therefore, strong emphasis must be placed on the selection of glass substrates for a chromatic?error?compensated DOE doublet. We present a simple but effective strategy to select substrates which allow the minimum etch depths for the DOEs. The selection depends on both the refractive index and the dispersion, and we apply it to design an achromatic DOE doublet for the Near?Infrared range as an integral part of an imaging optics. The introduction of a corridor in which the DOE phase shift is allowed to vary increases the spectral range for which the figures of merit indicate excellent performance.

9192-18, Session 4

Gradient index (GRIN) and homogeneous materials for multiband IR optics

Daniel J. Gibson, Shyam S. Bayya, Jas S. Sanghera, U.S. Naval Research Lab. (United States)

The list of available materials for refractive infrared (IR) optics operating at wavelengths greater than 1 µm has been quite limited when compared to materials available for visible systems. This typically presents a challenge for designers of IR imagers, one that is further complicated as new systems extend to multiple IR wavebands. NRL is developing new materials for refractive IR optics including new homogeneous IR glasses and ceramics as well as gradient index (GRIN) materials. The new materials transmit broad spectral regions and are suitable for use in multi-band imagers operating at wavelengths between 1 and 15 µm. The homogeneous (non-GRIN) materials cover a broad range of dispersions and partial dispersions thereby expanding the dispersion "glass map" for optical designers. GRIN optics offer potential for both weight savings and increased performance but commercial availability has so far been limited to visible and near-IR bands. The new IR GRIN materials are diffusion-based and have a delta-n of about 0.1. Design considerations, dispersion gradients, thermo-optic effects and physical properties of these materials are also presented and discussed.

9192-19, Session 4

"Moth's-eye" anti-reflection gratings on Germanium freeform surfaces

Meng Liu, Jason A. Shultz, Thomas J. Suleski, The Univ. of North Carolina at Charlotte (United States)

Germanium is commonly used for optical components in the infrared, but the high refractive index of germanium causes significant losses due to Fresnel reflections. Anti-reflection (AR) surfaces based on subwavelength "Moth's eye" gratings provide one means to significantly increase optical transmission. As found in nature, these gratings are conformal to the curved surfaces of lenslets in the eye of the moth. Engineered optical systems inspired by biological examples offer possibilities for increased performance and system miniaturization, but also introduce significant challenges in both design and fabrication.

In this paper, we consider the design and application of conformal Moth's eye AR structures on germanium freeform optical surfaces, including lens arrays and Alvarez lenses. Fabrication approaches and limitations based on both lithography and multi-axis diamond machining are considered as part of the design process. Incorporation of AR gratings on curved surfaces results in varying angles of incidence across the component that must be taken into consideration. We present rigorous coupled wave analysis simulations of designs in GSolver™ with less than 10% reflectance for angles of incidence up to 50 degrees. We also discuss the application of Fourier modal methods and adaptive field tracing approaches in LightTrans VirtualLab™ for simulation of subwavelength AR gratings and conformal, multi-scale optical systems.

9192-20, Session 4

Anti-reflective coatings making blooming for tunneling particles

Alexander Kaklyugin, Photron-Auto (France)

The optical phenomenon of enlightenment (of films, lenses, etc.) is generally known. Anti-reflective coatings are being widely used to reduce the light losses for passes through the optical surfaces. Similar problems for quantum particles passing through the potential barrier are considered.

The problem of the quantum barrier blooming (will use the term to distinguish from optics) by supplementing additional barriers is formulated. The task is able to solve analytically for the simplest case of barrier. The antireflection perturbation in the situation represents two singular potential wells. It is proved for specific range of barrier the effect of blooming takes place for any wave number values and obtained the wave number restriction for barriers out of the range. The possibility of blooming detuning of the quantum wells is considered. Dependences of the reflection and transmission coefficients are found as a function of the degree of detuning. It is shown that asymmetric detuned barrier loses the property of reciprocity: the properties of the barrier transparency are significantly dependent on the direction of propagation.

There is consider as an experimental example of a dielectric barrier with blooming additives in the form of absorbed layers of molecular oxygen playing the role of ?-like potential wells by means of O2- ion formation. It is expected such a barrier will selectively pass electrons with a specific energy.

The possibility of barrier building for selective passing atomic particles (atoms, ions, molecules) is considered too.

9192-21, Session 4

Stray light analysis and energy distribution description in high-power laser systems

Xiaotong Li, Zhaofeng Cen, Zhejiang Univ. (China)

Stray light in high power laser systems is harmful for laser beam transmission and system safety. Our software GA can analyze stray light and give the paths of ghost beam using the data structure of binary tree for ordinary systems or using multi-pork tree for the systems including diffraction components. Now the problem is how to describe and display the result so as to tell users friendly the surfaces which play the main role in stray light transmission. Because in the stray light tree some rays are with much larger energy than other rays especially in high power laser systems, usual display methods such as curves, gray graph or

false color graph can not enough to describe the stray light information. In our updated program we record the energy in traced rays, cut slices between two given surfaces and do the operation of adding energy at the responding grid position of each slice, then play the energy distribution animation from begin slice to the end repeatedly in gray or false color. When the user stops playing at a certain slice, the energy of a certain grid in current slice and its whole path can be displayed according to the user's command. In this paper we give the principles, methods, some program interfaces and examples, and give the conclusion that tracing a quantity of real ray is available for calculating real energy distribution when we have found a reasonable way of output or display.

9192-22, Session 5

3D head-mount display with single panel

Yuchang Wang, Junejei Huang, Delta Electronics, Inc. (Taiwan)

The head mount display for entertainment usually requires light weight. But in the professional application has more requirements. The image quality, FOV, color gamut, response and life time are considered items, too. A head mount display with single panel. It bases on the TI DMD spatial light modulator. The multiple light sources and splitting images relay system are the major design tasks.

The relay system images the object (DMD) into two image plane to crate binocular vision. The 0.65 inch 1080P DMD is adopted. The relay have a good performance which includes the doublet reduce the chromatic aberration. Some spaces reserve for placing the mirror and adjustable mechanism. The mirror splits the rays to the left and right image plane. These planes regard to the eyepieces objects then images to eyes. A changeable mechanism provides the variable interpupillary distance (IPD). And the folding optical path makes sure the HMD center of gravity is close to the head. Prevents the uncomfortable downward force been applied to head or orbit. Two RGB LED assemblies illuminate to the DMD in different angle. The light is highly collimated. And the divergence angle is small enough which one LED ray would only inter to the correct eyepiece. This switching is electronic control. There is no moving part to produce vibration and fast switch would be possible. Two LED synchronize with 3D video sync by a driving board which also control DMD. When the left eye image is displayed on DMD, the LED for left optical path turns on. Vice versa in right image and accomplish 3D scene.

9192-23, Session 5

Afocal viewport optics for underwater imaging

Dan Slater, Consultant (United States)

A conventional camera can be adapted for underwater photography by enclosing it in a waterproof pressure housing with a view port. The view port, as an optical interface between water and air needs to consider both the camera and seawater optical constraints while also providing a high pressure water seal. Hydrospace visibility is limited to short distances which drives a need for wide angle views. Practical optical interfaces between seawater and air range from simple flat plate windows to complex water contact lenses. This paper first provides a brief review of the ocean environment including design issues, optical characteristics and material tradeoffs. This is followed by a discussion including performance characteristics of various afocal underwater view port types including flat windows, domes and the Ivanoff corrector lens, a derivative of a Galilean wide angle camera adapter. Several new and interesting optical designs derived from the Ivanoff corrector are presented including a very compact dual mode (in water and in air) afocal corrector lens for a small digital still camera and an afocal underwater hyperhemispherical fisheye lens.

9192-24, Session 5

Vibration analysis and testing for the LLST optical module

Michele S. Weatherwax, Keith B. Doyle, MIT Lincoln Lab. (United States)

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A lunar orbiting space terminal was recently developed as part of NASA's Lunar Laser Communications Demonstration program. The space terminal uses a 10 centimeter, inertially-stabilized telescope and a 0.5 watt beam to transmit data at up to 622Mbps between the Moon and one of several ground terminals on Earth. Tight coupling between analysis and testing was conducted to ensure both performance and survival requirements were met in the operational and non-operational vibration environments. Performance requirements were driven by meeting demanding pointing stability requirements in the operational vibration environment of 4 urad. A highly-correlated FEA model was developed using vibration testing to extrapolate the behavior of the system beyond the practical limits of the vibration test bed. The launch load non-operational vibration environment was simulated through both analysis and testing using force-limiting to avoid over designing and testing the sensitive optics. The iterative and associated challenges of the vibration analysis and testing effort will be discussed that helped enable the successful launch, deployment, and ultimately demonstration of NASA's first space lasercom program.

9192-25, Session 5

Improved design of Raman-based optical sensor for the identification of oral cancer

Yashar Khodaei, Medhanie Tesfay, Erlangen Graduate School in Advanced Optical Technologies (Germany) and Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Christian Knipfer, Univ. Erlangen (Germany); Werner Adler, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Kathrin Brunner, Florian Stelzle, Univ. Erlangen (Germany); Stefan Will, Andreas Braeuer, Erlangen Graduate School in Advanced Optical Technologies (Germany) and Lehrstuhl für Technische Thermodynamik (Germany) and Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Background: Raman-Spectroscopy allows for a non-invasive and sensitive acquisition of the molecular composition of biological tissue through the in-elastic scattering of incident monochromatic light from matter. Raman spectroscopy thus can provide an objective "chemical fingerprint" of the examined region with high spatial resolution, which can be used for the identification of molecular changes through specific spectral patterns in oral cancer tissue. Our workgroup showed the potential of identifying oral squamous cell carcinoma with high sensitivity and specificity in an ex vivo setting with minimum alteration of natural conditions (0.86 and 0.94, respectively).

Objective: It was the aim of the study to improve data acquisition by using a fiber-probe with highly automated spectral data acquisition and analysis. Thus a robust and user-friendly system for physicians can be established which allows for a time-saving and cost-reducing application.

Materials and Method: The suppression of the fluorescence background was done with SERDS method followed by polynomial fit and a statistical method was implemented for the classification of the reconstructed Raman signal.

Results and Conclusion: The results of this study show the potential of utilizing Raman-based sensors and the automatic online processing of the acquired spectral data for enhanced clinical diagnosis.

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9192-26, Session 6

Packaging efficiency analysis of phosphor-converted white LEDs *(Invited Paper)*

Ching-Cherng Sun, Yu-Yu Chang, Cheng-Chien Chen, Ching-Yi Chen, National Central Univ. (Taiwan)

In this paper, we present a study of packaging efficiency for three different packaging structures. Simulation based on a developed phosphor model predicts the packaging loss in different packaging structures. The corresponding experimental measurement shows similar trend to the simulation, and the highest packaging efficiency of 69% is obtained. The analysis shows that in the best condition with reflectivity of 90% and absorption coefficient of 200 cm-1 in the active layer, the packaging efficiency can be as high as 75%. Higher packaging efficiency can be obtained if the packaging structure is optimized, and a phosphor with higher quantum efficiency is available. There is still a space to improve from 70% to 85%.

9192-27, Session 6

Optical design of low glare luminaire applied for tunnel light

Ming-Shiou Tsai, Ching-Cherng Sun, Yi-Chien Lo, National Central Univ. (Taiwan)

This paper proposes an optical design of tunnel light in one-way traffic. The luminaire shows high optical efficiency, low glare effect, good optical utilization factor, and high uniformity on the illuminated target region. All the above features meet the requests of regulations. A LED with a cluster package is used, and its accurate light source model is established first for designing the freeform TIR lens. Each surface of the freeform TIR lens has its specific function. For example, the light from the LED source can be modulated for reducing the glare effect, and the energy distribution is reorganized for obtaining a better lighting performance. By the comparisons between simulations and experiments, we verify that this design is workable.

9192-28, Session 6

Nonimaging achromatic lens design for LED direct-lit backlight applications

Meng-Che Tsai, Bo-Song Chen, Tsung-Xian Lee, National Taiwan Univ. of Science and Technology (Taiwan)

Nowadays, light emitting diodes(LEDs) have been widely used in backlight module for display technology. Most of researches tend to improve optical performance in specific applications, such as sufficient efficiency, desired intensity distribution and high illuminance uniformity. However, most of phosphor converted whited LEDs have the problem of inducing impure white light.The undesired phenomenon of yellow ring or blue ring becomes more serious through incorrect secondary optical design.

In this paper, we emphasize on enhancing the spatial color and illuminance uniformity of LED direct-lit backlight using nonimaging achromatic lens design. We propose a new design method to re-distribute and uniform the ratio of blue and yellow light on the target surface. Moreover,we further apply it in direct-lit LED backlight lens design, in which the uniformity of illuminance on the out coupling surface can be as much as 75% and the color uniformity (Δu'v') is improved to 0.008. Therefore, the result of high color and illumination uniformity can be achieved simultaneously.

9192-29, Session 6

A novel method for designing dichroic color filter transmittance curves for lighting applications

Rui Qi, Frank Shum, Soraa, Inc. (United States)

This paper focuses on designing dichroic filters for changing the color of lighting-emitting diode (LED) lamps. Dichroic filters are composed of multiple dielectric layers on a substrate. By applying a dichroic filter, some of the LED's spectral energy is reflected and some is transmitted, which changes the lamp's color. Conventional methods to obtain spectral transmittance curves have shortcomings. The design criteria for the transmittance curves are incompatible with the metrics used in lighting applications, such as correlated color temperature (CCT) and color rendering index (CRI). Thus, the color rendering performance and the optical transmission of a lighting system are not optimized. This observation leads to the development of a proposed method for designing dichroic filter transmittance curves to provide accurate color shift, high CRI, and sufficient optical transmission. The method initially uses the transmittance curve of an existing color filter that provides a roughly close color shift for the LED lamp to calculate the transmittance curve that causes an accurate color shift by polynomial approximation. Based on the approximated curve, a preliminary transmittance curve without the effect of the LED lamp's secondary optics is derived and verified in thin-film design and optical design software tools. Further, the derived preliminary transmittance curve is optimized by applying an algorithm to loop through a large amount of representative curves fluctuating near the preliminary curve. The resulting dichroic filter provides an accurate color shift (?CCT = –600±50K, Duv =± 0.003), high CRI (Ra and R9 >= 95), and sufficient luminous flux transmission (>= 70%).

9192-30, Session 6

Six-color solid state illuminator for cinema projector

Junejei Huang, Yuchang Wang, Delta Electronics, Inc. (Taiwan)

Light source for cinema projector requires reliability, high brightness, good color and 3D for without silver screens. To meet these requirements, a laser-phosphor based solid state illuminator with 6 primary colors is proposed. The six primary colors are divided into two groups and include colors of R1, R2, G1, G2, B1 and B2. Colors of B1, B2 and B2 come from lasers of wavelengths 445 nm, 465 nm and 639 nm. Color of G1 comes from G-phosphor pumped by B1 laser. Colors of G2 and R1 come from Y-phosphor pumped by B2 laser. Two groups of colors are combined by a multi-band filter and working by sequentially switching B1 and B2 lasers. The combined two sequences of three colors are sent to the 3-chip cinema projector and synchronized with frame rate of 120Hz. In 2D mode, the resulting 6 primary colors provide a very wide color gamut. In 3D mode, two groups of red, green and blue primary colors represent two groups of images that received by left and right eyes. The whole illuminator forms a compact module in which semiconductor lasers of wavelength 445 nm, 465 nm and 639 nm are formed by diode array, "VECSELs" and "bars", respectively and multi-band filter is formed by reflecting bands of (B2, G2, R1) and transmitting bands of (B1, G1, R2). By replacing the conventional UHP lamp in the existing 0.95" DMD 3-chip engine with this SSI module, outputs of 5000 lm at 3D mode and 10k lm at 2D mode can be achieved.

9192-31, Session 6

The analysis of different blue light sources for YAG phosphor optical model

Yu-Yu Chang, Ching-Yi Chen, Guan-Ting Kuo, Ruei-Lin Huang, Tsung-Hsun Yang, Ching-Cherng Sun, National Central Univ. (Taiwan)

In this paper, we propose and demonstrate a well-defined YAG phosphor optical model with thermal prediction. Different blue light sources will correspond to different excitation abilities of YAG phosphor. Therefore, the absorption coefficient and conversion efficiency will also be different. When LEDs turn on, the heat will be inevitably generated at the same time. Thermal problem will occur from blue LED die and phosphor. Accordingly, a modified YAG phosphor optical model with temperature effect is required. Depending on the measurement of spectra with rising temperature, related absorption coefficient and conversion efficiency can be inserted in all range of modelized blue light sources for YAG phosphor optical model. In the range from 429 nm to 464 nm of blue light sources, the chromaticity errors between experiment and simulation are all smaller than 0.02. The phosphor model is useful to accurately simulate the power ratio of the blue and yellow lights emitted by the white LEDs and is important in white LED package.

9192-32, Session 7

Fabrication of heterogeneous microlenses using self-surface tension

Cheng-Han Chiang, Guo-Dung Su, National Taiwan Univ. (Taiwan)

In recent years, light emitting diodes (LEDs) are applied in general lighting in large volume, mostly in territory of backlight lighting. Therefore, our research is focused on backlight illuminance. We make the light field intensity more uniform by utilizing heterogeneous micro lens array (MLA) to approximate the shape of a freeform lens which constructed by the energy conservation principle. In this paper we propose novel fabrication of convex and concave microlenses on the same surface. We utilize diluted SU-8 photoresist in an inkjet-printer and apply the hydrophilic confinement of SU-8 photoresist after UV/Ozone and self-surface tension to make heterogeneous microlenses. Then we use an 3D-printer and replication process to fabricate the module of micro lens array (MLA) to achieve uniform LED lighting in a back light unit.

9192-33, Session 7

Miniaturized camera system for an endoscopic capsule for examination of the colonic mucosa

Frank C. Wippermann, Martin Müller, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Martin Wäny, AWAIBA Lda. (Germany); Stephan Voltz, AWAIBA GmbH (Germany)

Today´s standard procedure for the examination of the colon uses a digital endoscope located at the tip of a tube encasing wires for camera read out, fibers for illumination, and mechanical structures for steering and navigation. On the other hand, there are swallowable capsules incorporating a miniaturized camera which are more cost effective, disposable, and less unpleasant for the patient during examination but cannot be navigated along the path through the colon. We report on the development of a miniaturized endoscopic camera as part of a completely wireless capsule which can be safely and accurately navigated and controlled from the outside using an electromagnet. The endoscope is based on a global shutter CMOS-imager with 640x640 pixels and a pixel size of 3.6µm featuring through silicon vias. Hence, the required electronic connectivity is done at its back side using a ball grid array enabling smallest lateral dimensions. The layout of the f/5-objective with 100° diagonal field of view aims for low production cost and employs polymeric lenses produced by injection molding. Due to the need of at least one-time autoclaving, high temperature resistant polymers were selected. Optical and mechanical design considerations are given along with comprehensive experimental data of achieved resolution versus object distance, distortion, and relative illumination obtained from realized demonstrators.

9192-34, Session 7

Stability of glass versus plastics for transmissive high-power LED optics

Christian Paßlick, Ansgar Hellwig, Marc C. Hübner, Ulf Geyer, Thomas Heßling, Auer Lighting GmbH (Germany)

In the past, the major part of transmissive LED optics was made out of injection molded polymers like PMMA. Recent LED developments now show constantly increasing levels of luminous flux and energy densities, which restrict the usability of such polymer optics due to their thermal stability limitations. As an example, thermal simulations have shown that light guiding/mixing structures (rods) made out of polymer materials easily reach temperatures above their melting point due to their absorption characteristics. However, there is a great demand for such light rods from the automotive and entertainment industry and thus glass is becoming of great interest as an optical material again.

Glass has typical transformation points of hundreds of degrees Celsius and therefore withstands higher temperatures without any problems. Exceptional scratch resistance, extreme resistance against all hydrocarbons, weathering effects and in particular against internal or external UV light (from the light source itself or from solar radiation) are just some of the many further advantages of glass, especially for outdoor and automotive applications.

This contribution should present some comparable thermal simulations by means of the Finite Element Method for a light conductor as an example and should give corresponding assistance for an appropriate material selection for high-power LED optics.

9192-35, Session 7

Surface micro-structuring of glassy carbon for precision glass molding of diffractive optical element

Karin Prater, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Julia Dukwen, Fraunhofer Institute for Production Technology (Germany); Toralf Scharf, Hans P. Herzig, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Andreas Hermerschmidt, HOLOEYE Photonics AG (Germany)

Glassy carbon is used nowadays for a variety of applications because of its properties such as mechanical strength, thermal stability and non-sticking adhesion. This makes it a suitable candidate as a mold material for precision compression molding of low and high glass-transition temperature materials.

We introduce a process that allows micro-structuring of glassy carbon by O2/SF6 reactive ion etching. We discuss the uniformity, surface roughness, edge definition and lateral resolution which are the most relevant parameters for a stamp in applications in optics.

The use of titanium as a hard mask allows achieving a reasonable selectivity of 4:1, which has so far been one of the main problems in micro-structuring of glassy carbon. A drawback of using a hard mask is that the additional fabrication steps are required. The structuring of the titanium layer is done by Cl2/BCl3 reactive ion etching. We investigate the titanium surface structure with its 5-10nm-thick layer of TiO2 grains and its influence on the hard mask shape.

In our fabrications, we were able to realize optically flat diffractive

structures with slope angles of 80° at typical feature sizes of 5 micron and 700 nm depth qualified for high precision glass molding.

The fabricated GC molds were applied to thermal imprinting onto glass.

GC molds with 1mm and 3mm thickness were tested with binary and multilevel structures. We discussed the suitability of the fabricated GC samples as molds for cost efficient mass production with a high quality.

9192-36, Session 7

Manufacturing of the integrated microlenses via direct laser writing for the light flow control of UV LEDs

Albertas Žukauskas, Arūnas Kadys, Roland Tomašiūnas, Mangirdas Malinauskas, Vilnius Univ. (Lithuania)

We report on the manufacturing of the microoptical elements integrated on the sapphire substrates for the enhancement of the InGaN/GaN LED's light extraction and directionality. Circular (radius – 50 µm) and square shaped (70 ? 70 µm2) aspherical lenses were designed according to thin lens approximation. Two cases of the light flow control were considered: focusing (concentration) and collimation. Single microoptical elements and 100 % fill factor arrays thereof were fabricated via fs laser direct writing of non-photosensitized hybrid polymer SZ2080 depending to ORMOSIL materials class. Material properties important for optical applications were determined - the influence of photoinitiator concentration and absence of it to laser induced optical damage threshold, refractive index, and transmission. The increase of the damage threshold ten and two folds of the pure polymer at ns and fs pulse regimes at second harmonics (532 nm and 515 nm wavelengths) was noticed. Absorbance at 400 nm widely used in blue LED's was found negligible in pure material while it was significant in the photosensitized sample. The optical and spectral performance of the fabricated microstructures has been measured experimentally and efficient focusing and collimation of the light from LEDs was demonstrated. In addition, the study of the laser repetition rate influence to structuring in sense of dominating photo-polymerization mechanism was performed and the obtained results are discussed. The experiments were carried out tuning 300 fs pulse duration Yb:KGW laser system's repetition rate from 1 kHz to 200 kHz. Potential application of the microlenses for the light extraction from LEDs is discussed and preliminary results are presented.

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9193-1, Session 1

What does a wave-optically impossible light-ray field look like?

Paul Stockman, Stephen Oxburgh, Univ. of Glasgow (United Kingdom); Tomas Tyc, Masaryk Univ. (Czech Republic); Johannes Courtial, Univ. of Glasgow (United Kingdom)

Ray-optically, optical components change a light-ray field on a surface immediately in front of the component into a different light-ray field on a surface behind the component. In the ray-optics limit of wave optics, the incident and outgoing light-ray directions are given by the gradient of the phase of the incident and outgoing light field, respectively.

But as the curl of any gradient is zero, the curl of the light-ray field also has to be zero.

The above statement about zero curl is true in the absence of discontinuities in the wave field. But exactly such discontinuities are easily introduced into light, for example by passing it through a glass plate with discontinuous thickness. This is our justification for giving up on the global continuity of the wave front, thereby compromising the “quality” of the field (which now suffers from diffraction effects due to the discontinuities) but also allowing light-ray fields that appear to be (but are not actually) possessing non-zero curl and thereby significantly extending the possibilities of optical design.

Here we discuss how the value of the curl can be seen in a light-ray field. As curl is related to spatial derivatives, the curl of a light-ray field can be determined from the way in which light-ray direction changes when the observer moves. We demonstrate experimental results obtained with light-ray fields with zero and apparently non-zero curl.

9193-2, Session 1

Phase space imaging in optical design

Denise Rausch, Alois Herkommer, Univ. Stuttgart (Germany)

In the last years the demand for high performance optical system with a high accuracy increased for a lot of different industrial applications fields like medical science, automotive technologies or high efficiency solar concentrators. Therefore, the need of more complex optical designs forces the designer to follow new paths. The concept of phase space in optical design is a new effective method to evaluate the performance of an optical system. Especially, in the design of freeform surfaces for imaging and non-imaging applications, the phase space provides a new access. For these complex systems it is important to have access to illumination quantities like irradiance, radiance, etendue and energy to check the performance of the optical system. These quantities can directly be illustrated in phase space. The difficulty is to find ways to illustrate the angular and spatial distribution not only in two dimensions but also in four dimensions which is important because of the complex, non-rotational shape of freeform surfaces. We present examples of this phase space imaging and show how the shape of the freeform surfaces impacts and modulates the spatial and angular spectrum of the light field. Another advantage is that the etendue, which characterizes how spread the light is, can directly be seen as a volume in phase space and be investigated when light is propagating through an optical system. In perspective the phase space concept can be used to find a surface shape for a given target phase space distribution by calculating backwards, especially for non-uniform illumination.

9193-3, Session 1

Monolithic all fiber optic Fourier transform aperture

Jeffrey J. Perkins, Craig Richardson, Don Russell, Charles R. Schabacker, Fiberguide Industries, Inc. (United States)

By cleaving and fusing a series of graded index lenses to fused silica optical fiber, it is possible to create a monolithic 4F imaging system. By using configurations of multiple fibers, complete control over the numerical aperture of an input beam, and the resulting Fourier transform of the optical phase space, can be achieved. We discuss the paradigm of this new shaping system in terms of fractional Fourier transforms introduced by graded index lenses, in combination with selective aperturing of the the rotated phase space, it is possible to create novel optical phase spaces. Experimental results will be reported.

9193-4, Session 1

Windows into non-Euclidean spaces

Stephen Oxburgh, Christopher D. White, Georgios Antoniou, Lena Mertens, Christopher Mullen, Jennifer Ramsay, Duncan McCall, Johannes Courtial, Univ. of Glasgow (United Kingdom)

Two microlens arrays that are separated by the sum of their focal lengths form arrays of micro-telescopes. Parallel light rays that pass through corresponding lenses remain parallel, but the direction of the transmitted light rays is different. This remains true if corresponding lenses do not share an optical axis (i.e. if the two microlens arrays are shifted with respect to each other). The arrays described above are examples of generalised confocal lenslet arrays, and the light-ray-direction change in these devices is well understood [S. Oxburgh et al., Opt. Commun. 313, 119 (2014)].

Here we show that such micro-telescope arrays change light-ray direction like the interface between spaces with different metrics. To physicists, the concept of metrics is perhaps most familiar from General Relativity (where it is applied to spacetime, not only space, like it is here) and Transformation Optics [J. B. Pendry et al., Science 312, 1780 (2006)], where different materials are treated like spaces with different optical metrics. We illustrate the similarities between micro-telescope arrays and metric interfaces with raytracing simulations.

Our results suggest the possibility of realising transformation-optics devices with micro-telescope arrays, which we investigate elsewhere.

9193-5, Session 1

Retrospectives and perspectives in telecentric imaging lens design

Irina L. Livshits, Sergey Okishev, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Telecentic lenses are widely used for machine vision, metrology, optical lithography, etc., this explains why these optical systems are still “wanted” in spite of long history of creating such systems.

This topic is of a big interest both in field of design and optimization. Taking into consideration growing requirements for new telecentric lenses, the presence of many local minima in the optical merit function landscape makes design non-trivial. We tried many different starting points for telecentric lens design and would recommend to start it with two-part design, which is specially helpful for double-telecentric lenses.

For comparison we present designs for the simplest and most complex telecentric lenses.

Among the most important aberrations we name "distortion", because the object and image must have high requirements to it's similarity, which impossible to achieve in case of big distortion.

Modern telecentric lenses work together with digital cameras, so, they have to be designed together as a one opto-electronic system taking into consideration all characteristics of the camera. In this case, important performance criterion is determined from the camera pixel size.

Talking about length, diameter and other mechanical contrains we found out that this objectives are relatively long since the stop is in the rear focal plane of a telecentric objective it is usually a quite long objective. Since the Chief Ray is parallel to the optical axis, the lens diameter of the front lens is at least the size of the object field plus 2*NA. That makes telecentric lenses usually quite large in diameter as well.

We present examples with detailed explanation on most popular telecentric lenses and elements to use.

9193-6, Session 2

Anamorphic stretch transform for analog and digital compression of big data *(Invited Paper)*

Bahram Jalali, Mohamad Asghari, Univ. of California, Los Angeles (United States)

Telecommunication systems routinely generate, capture and analyze data at rates exceeding billions of bits per second. Interestingly, the scale of the problem is similar to that of blood analysis. With approximately 1 billion cells per milliliter of blood, detection of a few abnormal cells in a blood sample translates into a "cell error rate" of 10-12, a value that is curiously similar to the bit error rate in telecommunication systems.

Motivated by WDM and the time-stretch technique, a new type of bright-field camera known as STEAM has demonstrated imaging of cells with record shutter speed and throughput leading to detection of rare breast cancer cells in blood with one-in-a-million sensitivity. A second technique called FIRE is a new approach to fluorescent imaging that is based on wireless communication techniques. FIRE has achieved real-time pixel readout rates one order of magnitude faster than the current gold standard in high-speed fluorescence imaging.

Producing data rates as high as one Tera bit per second, these real-time instruments pose a big data challenge that overwhelms even the most advanced computers. Driven by the necessity of solving this problem, we have recently introduced and demonstrated a categorically new data compression technology. The so called Anamorphic Stretch Transform is a physics based compression technique that not only performs real-time data compression in the analog domain, but can also function as a digital algorithm for compression of images with superior performance to JPEG and other compression technologies. It alleviates the big data problem in real-time instruments, in digital imaging and beyond.

9193-7, Session 2

Formal analysis of electromagnetic optics

Sanaz Khan Afshar, Osman Hasan, Sofiène Tahar, Concordia Univ. (Canada)

Optical systems are increasingly used in microsystems, telecommunication, medicine, spectroscopy, laser industry, aerospace, and military technologies. Due to the complexity and sensitivity of optical systems, their verification raises many challenges for engineers. Traditionally, the analysis of such systems has been carried out by paper-and-pencil based proofs and numerical computations. However, these techniques cannot provide %100 accurate results due to the risk of human error and inherent approximations of numerical algorithms. In order to overcome these limitations, especially in safety-critical applications, we propose to employ theorem proving as a complement to computational and numerical approaches to improve optical system analysis in a comprehensive framework. Theorem proving is a computer-based technique in which the system model and specification, both, are expressed in one suitable logic, and, using mathematical reasoning, a proof is constructed that the system model reflects the specification. This paper presents a higher-order-logic (a language used to express mathematical theories) formalization of electromagnetic optics in the HOL Light theorem prover. Based on an extension of the multivariate analysis library of HOL Light, we formalize the notion of electromagnetic fields and mediums. This allows us to derive general theorems about the behaviour of light at any interface and through mediums, based on electromagnetic theories. In order to demonstrate the practical effectiveness of our approach, we present the analysis of resonant cavity enhanced photonic devices, focusing on the light intensity of a laser and the quantum efficiency of a photo-detector.

9193-8, Session 2

Digital image processing for wide-angle highly spatially-variant imagers

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Monocentric lenses are superior in performance over other wide field of view lenses in that they allow for lower F/#'s and they do not suffer from coma, astigmatism or field dependent distortion. Monocentric lenses do, however, form a hemispheric image plane which is incompatible with current sensor technology. In order to overcome this obstacle it is possible to relay the curved image plane to flat image sensors using fiber optic bundles. This solution requires image processing to correct for artifacts inherent to fiber bundle image transfer. We present digital image processing techniques used to stitch together image data from individual sensors, correct for sphere to plane mapping distortion, and remove artifacts due to fiber cladding, absorbers and broken fibers within the fiber bundles. We extended the functionality of the system by using a single exposure captured during a focal sweep of the image sensor to produce an extended depth of focus (EDOF) image. An in depth characterization of the transfer function, and point spread function measurements of the imaging components supports the methods used and provides insight into the overall system performance. The processed images from the fiber coupled monocentric lens imager are compared to images taken using a commercial camera with comparable F/# and field of view (FOV).

9193-9, Session 2

Research on the feature extraction and pattern recognition of the distributed optical fiber sensing signal

Bingjie Wang, Shaohua Pi, Fudan Univ. (China)

Abstract—Distributed optical fiber sensor technology has been developed rapidly in recent years. Feature extraction has a very important impact on the accuracy of pattern recognition. In this paper, feature extraction and pattern recognition of the distributed optical fiber sensing signal have been researched. We adopt Mel-Frequency Cepstrum Coefficient (MFCC) feature extraction, wavelet packet energy feature extraction and wavelet packet Shannon entropy feature extraction methods to obtain sensing signals (such as speak, walk, and wind signals) characteristic parameters respectively, and perform pattern recognition using RBF neural network afterwards. The performance of these three feature extraction methods are compared. We choose MFCC characteristic vector to be 12-dimensiona. The signals are decomposed into four and five layers by db wavelet packet transform, which respectively extract 16 and 32 frequency constituents as

characteristic vector. In the process of pattern recognition, keeping the same samples for testing the algorithm, changing the number of training samples and the value of diffusion coefficient has a great influence on identification accuracy. The results of the wavelet packet Shannon entropy 32 dimensional characteristic vector is less satisfactory, and that of MFCC 12 dimensional characteristic vector are worse, but has a high computational speed. The results using wavelet packet energy feature extraction are unstable, and that of wavelet packet Shannon entropy 16 dimensional characteristic vector can give the best recognition result with 98% accuracy, which is significantly higher than other published results for the same task.

9193-41, Session 2

The analysis and design of multiple phase plane for wavefront coding system

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For traditional wave front coding (WFC) system, a single phase plate which is on the aperture stop of normal optical system modulates the phases of all light rays. The WFC can extend the depth of field and obtain the clear image through blurring and decoding image. The size of the aperture stop is relatively small for the normal optical system, but the depth of field is relatively wide and can be extended more long by WFC. For the large size of aperture optical system, the depth of field is very narrow, and the aberration of edge field of view and distortion are terrible, which is not beneficial to using WFC to decode the image and extend the depth of field because of the amplification of aberration and distortion with the WFC. To solve this problem, according to the aberration theory, we analyze the types, characteristics and distribution of the aberration of large aperture optical system. According to the theories of the WFC and the information optics, we also analyze the characteristics and distribution of the traditional WFC system. For the above all, in this paper, the multiple phase plane of wave front coding technology, is applied in the large aperture optical system. The simulation shows that the novel technology with multiple phase planes can extend not only the depth of field but also the size of aperture stop, which solves the problem of the traditional WFC is not applied in the large aperture optical system. It also shows that with the technology of multiple phase planes, the depth of field is extended to 4 times of the original system, and the size of aperture is 3 times. It is concluded that with the multiple phase planes, the system can obtain more information of object space.

9193-10, Session 3

Stereo matching image processing by synthesized color and the characteristic area by the synthesized color

Akira Akiyama, Kanazawa Technical College (Japan); Eiichiro Mutoh, The Society of Japanese Aerospace Companies (Japan); Hideo Kumagai, Tamagawa Seiki Co., Ltd. (Japan)

We have studied the stereo matching image processing by synthesized color and the characteristic area by the synthesized color for ranging the object and image recognition.

The typical images from a pair of the stereo imagers may have some image disagreement each other due to the size change, missing place, appearance and deformation of characteristic area.

We construct the synthesized color and characteristic color area with same synthesized color to make the distinct stereo matching.

The construction of the synthesized color and characteristic color area with same synthesized color follows the next 3 steps.

The first is making binary edge image by differentiating the typical image from each imager and verifying that differentiated image has normal density of frequency distribution. The procedures of differentiating are such as Daubechies wavelet transformation, first differential operation, Sobel operation, Laplacian operation and etc.

The second is averaging color brightness between binary edge points with respect to horizontal direction and vertical direction alternatively. The averaging color procedure is done many times until the fluctuation of averaged color become negligible.

The third step is extracting area with same synthesized color by counting the pixel number of same synthesized color brightness and grouping these pixel points by 4 directional connectivity relations.

The matching places for the stereo matching are the boundary lines of the characteristic color areas and the color areas. The parallaxes between matching places and the color areas are used for ranging the characteristic areas. The experiments of the stereo matching by the synthesized color technique give the distinct stereo matching for ranging.

9193-11, Session 3

A combined simulation approach using ray-tracing and finite-difference time-domain for optical systems containing refractive and diffractive optical elements

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Optical and photonic devices often comprise optical elements which interact with light on different geometric length scales, ranging from (sub-)wavelength to several millimeters. Well-established physical models exist to describe coherent or incoherent effects, like refraction or diffraction including polarization effects, which form the basis for several simulation approaches. While at dimensions much larger than the light wavelength the incoherent ray-tracing techniques are commonly used, at dimensions in the (sub)-wavelength regime simulation tools like the Finite-Dfference Time-Domain (FDTD) method are indispensable, as they allow for the simulation of coherence effects where phase relations play a crucial role.

The two approaches are structurally entirely different, so that a proper description for the macroscopic and the (sub-)wavelength scale at once would only work by connecting the two approaches together, exploiting the best of both in a step-by-step simulation. Unfortunately, there are no well-defined criteria for a switching from one method to the other and the development of appropriate selection criteria for exchanging data is a major issue to avoid error propagation. The output parameters of one simulation method can be used to provide the input parameters for the other one; in doing so, one needs to consider that these interface parameters have to be chosen carefully to ensure mathematical and physical consistency. In this contribution, a simulation approach is presented which combines classical ray-tracing and FDTD in the sense described above, enabling a joint simulation of optical systems containing both multiple diffractive and refractive optical elements. We discuss the methodology of our approach, and make a comparison between simulation results and experimental measurements. In addition, the simulation criteria and the applicability of our approach are theoretically examined.

9193-12, Session 3

Open-source fiber laser and amplifier design toolbox using custom FDTD simulation engine

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Fast and accurate numerical simulators allow efficient design and construction of fiber lasers and amplifiers, providing prediction and analysis tools that allow a fully closed loop design process. Here we present an open-source Matlab toolbox for designing and analyzing fiber lasers and amplifiers. Using a custom FDTD simulation engine, the software calculates optical power throughout the fiber as a function of space, time and wavelength. A wide range of analysis plots can be generated against several design variables, including pump and signal powers and wavelengths, coupler reflectance, fiber length, etc. This allows the designer to quickly understand the impact of varying the pump and signal inputs, and the physical layout of the fiber system.

The FDTD engine simultaneously solves the laser rate equations and the propagating wave equations to model the optical power in fiber lasers and amplifiers as a set of coupled PDE BVPs. The FDTD engine uses an FTCS Lax-Wendroff solver, modified to provide second-order accuracy in both time and space for fast convergence. Both steady-state (CW) and dynamic (pulsed, modulated) pump and signal inputs are considered, and arbitrary pump, signal, and ASE wavelengths are allowed. Default values are included for erbium- and ytterbium-doped fiber, and both core- and cladding-pumped systems are natively supported.

Comparison to experiment and literature are provided for validation.

9193-13, Session 3

LED source modeling and rayset generation from luminance maps *(Invited Paper)*

Peter I. Goldstein, Philips Color Kinetics (United States)

In the solid-state lighting industry, optical components are designed using simulations of Light Emitting Diodes (LEDs). The accuracy of the simulation depends on a reliable LED source model. Several commercial products measure LEDs by taking photographs and generate source models comprised of rayset data. However, little is published about the details of how rayset data are generated, and such details are often proprietary. Optical engineers and the solid-state lighting industry can benefit from a deeper understanding of the assumptions and limitations of currently available LED measurement systems. This paper details one process for generating rayset data from a series of photographs of an LED. It also discusses the assumptions and limitations of rayset generation. The quality of a rayset is limited by mechanical precision of the measurement process, angular resolution of the measurements, and the rayset generation algorithm.

9193-14, Session 3

Structural-thermal-optical-performance (STOP) model development and analysis of a field-widened Michelson interferometer

Salvatore J. Scola, James Osmundsen, Luke Murchison, Warren Davis, Joshua Fody, Charles Boyer, Anthony Cook, Chris Hostetler, NASA Langley Research Ctr. (United States); Shane Seaman, National Institute of Aerospace (United States); Ian Miller, LightMachinery Inc. (Canada); Wayne Welch, Adam Kosmer, Welch Mechanical Designs, LLC (United States)

An integrated Structural-Thermal-Optical-Performance (STOP) model was developed for a field-widened Michelson interferometer which is being built and tested for the High Spectral Resolution Lidar (HSRL) project at NASA Langley Research Center (LaRC). The performance of the interferometer is highly sensitive to thermal expansion, changes in refractive index with temperature, temperature gradients, and deformation due to mounting stresses. Hand calculations can only predict system performance for uniform temperature changes, under the assumption that coefficient of thermal expansion (CTE) mismatch effects are negligible. An integrated STOP model was developed to investigate the effects of design modifications on the performance of the interferometer in detail, including CTE mismatch, and other three dimensional effects. The model will be used to improve the design for a future spaceflight version of the interferometer. The STOP model was developed using the Comet SimApp(TM) Authoring Workspace, which performs automated integration between Pro-Engineer®, Thermal Desktop®, MSC Nastran™, SigFit(TM), CodeV(TM), and MATLAB(R). This is the first flight project LaRC has utilized Comet, and it allowed a larger trade space to be studied in a shorter time than would be possible in a traditional STOP analysis. This paper will describe the development of the STOP model, present a comparison of STOP results for simple cases with hand calculations, and present results of the correlation effort to bench-top testing of the interferometer. A trade study conducted with the STOP model which demonstrates a few simple design changes that can improve the performance seen in the lab will also be presented.

9193-15, Session 3

The refractive lens light source heat absorption and thermal aberration analysis

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The optical system in high energy light source, the optical system refractive lens is absorption the heat from light source.

The lens is absorption heat from light, and transfer the heat to surrounding by conduction.

The heat transfer will cause lens temperature difference and introduce optical aberration in optical system.

This study is trying to calculate the heat absorption ratio and temperature distribution in the lens.

The light source energy from each rays can weighted to finite element grids, and calculated thermal distribution in the lens.

The optical system rays through lens position are calculated by ray tracing, in different field of view.

The lens temperature distribution is weighted to each incidence ray path, and the thermal OPD is calculated.

The thermal OPD on the optical axis is transferred to optical aberration by fitting OPD and the Zernike polynomial.

The aberration results can be used to evaluate the thermal effect on the correct lens assembly in the telescope system.

9193-16, Session 4

Focus tunable mirrors made by ionic polymer-metal composite

Chung-Min Li, Guo-Dung Su, National Taiwan Univ. (Taiwan)

Ionic polymer metal composite (IPMC) could be used as a deformable mirror for optical modules. This material has the advantage that it can be easily driven at lower voltage compared to other devices and can achieve excellent optical tuning power. By changing the curvature of the mirror, it can show the effect of zooming. However, IPMCs need ionic hydration to operate, the degree of hydration of the IPMC is critical for its effective working as a motion actuator. As liquids evaporate in the air gradually, the displacement of IPMC will decrease, finally, IPMC will lose its function because of insufficient hydration. If IPMC is hydrated again, it will recover from its initial actuation performance, in other words, reliability is a challenge. Therefore, an encapsulation process for IPMCs is a critical subject to their practical use.

By designing a special packaging frame, IPMC can be actuated continuously until liquid dries out. The frame contains two parts, one is rectangular frame which helps IPMC mirror to locate at right position inside of optical modules, the other is outside of the modules and cuboid-like, where the center is hollow so that it can inject some ionic liquids into this hollow cuboid and make IPMC to be hydrated. Therefore, if we continue supplying ionic liquids, IPMC deformable mirrors can be used for longer time in air.

9193-17, Session 4

Stability of the micromachined membrane deformable mirror as a freeform optical element

Gleb V. Vdovin, Flexible Optical B.V. (Netherlands) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Oleg Soloviev, Vsevolod Patlan, Flexible Optical B.V. (Netherlands)

Micromachined membrane deformable mirror (MMDM) can serve as an “ad hoc” free-form optical element. To test the repeatability and stability of the standard MMDM, we have conducted the test of surface figure during multiple thermal cycling, test of figure drift at elevated temperatures, and a long-term 16-day stability test of actively formed mirror figure. The average rms error did not exceed lambda/25 at lambda = 633 nm, after cycling from -14 to +70 degrees C with return to the room temperature. The existing design provides lambda/10 stability in the temperature range of 10 degrees. Optimization of the design, eliminating astigmatism, would allow to extend the temperature range to about 30 degrees C. The long-term mirror figure instability at a constant temperature reaches lambda/20 rms in 16 days. The P-V error with respect to the nearest sphere changes from lambda/20 in the fiirst day, to about lambda/10 in the 16-th day. The tests

show that MMDM is stable enough to make a reasonable alternative to free-form optics in applications that require various optical shapes to be formed with a single element.

9193-18, Session 4

Compact touchless fingerprint reader based on digital variable-focus liquid lens

Gary C. Tsai, Lustrous Electro-Optics Co. Ltd. (Taiwan); Pei-Jen Wang, J. Andrew Yeh, National Tsing Hua Univ. (Taiwan)

Identity certification in the cyberworld has always been troublesome if critical information and financial transaction must be processed. Biometric identification is the most effective measure to circumvent the identity issues in mobile devices. Due to bulky and pricy optical design, conventional optical prism fingerprint readers have been discarded for mobile applications. In this paper, a digital variable-focus liquid lens was adopted on a camera for capturing of a floating finger via fast scanning multiple focal planes. Therefore, only putting a finger freely in front of a camera could fulfill the identity certification process. This fingerprint reader scans multiple focal planes from 1 cm to 5 cm in 0.3 second. Through examining the image qualities of multiple images at various focuses, one clear fingerprint image could be selected for extraction of fingerprint minutiae to certify the identity. In the optical design, a webcam is mounted with a liquid lens serving for fast-scan of fingerprint. The liquid lens based on the principle of driving two dielectric fluids via controlled electric field is redesigned in digital electrode structure with digital driving voltages. Under the digital operation, the switch time between two different focus of the liquid lens could be fast in milliseconds. The reader could maintain the similar size of a front camera of a cellphone. New variable-focus lens modules could be optimized for focus of fingerprint, palm and face features so that this reader can be readily used for full biometric identification purposes.

9193-19, Session 4

Reliability of ionic polymer metallic composite for optomechanical applications

Chungyi Yu, Guo-Dung Su, National Taiwan Univ. (Taiwan)

Electroactive polymer (EAP) is capable of exhibiting large property changes in response to electrical stimulation. EAPs can produce large deformation with lower applied voltage for actuation. IPMC (Ionic Polymer Metal Composite) is a well-known type of ionic EAPs. It has numerou attractive advantages, such as low electrical energy consumption and light weight. The mechanism of IPMC actuator is due to the ionic diffusion when the voltage gradient is applied, so that the type of ionic solution has a large impact on the physical properties of IPMC. In this paper, reliability tests of IPMC with several different ionic solution are demonstrated. Conventional IPMC with LiOH aqueous solution exhibits the best maximum displacement, but the water in LiOH solution is electrolyzed because of low electrolysis voltage 1.23 V of water. To improve electrolysis problems and the operation time in the air, proper solvents including high electrolysis voltage and low vapor pressure should be chosen. The reliability tests focus on the lifetime of IPMC in air. The blocking force, displacement and response time of IPMC will also be presented. More improvements of IPMC fabrication can be further developed based on studies in this paper.

9193-20, Session 4

An adaptive achromatic doublet design by double variable focus lenses

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Chromatic aberration is a typical problem in the lens design field, which is caused by the fact that the refractive index varies with the wavelength of light. As a result, the captured image looks blurred and the edges are noticeable colored. To correct the chromatic aberration, the widely accepted proposal is an achromatic doublet which combining a low-relative-dispersion element and a high-relative-dispersion element. The fundamental principle is the high-relative-dispersion element performs a little bit weak and negative power against the sign of the whole lens, so that two different wavelengths of light could be brought to a common focus and the chromatic aberration could be minimized and corrected.

Variable-focus lens is a novel and attractive topic that a single lens cell could dynamically change its optical power. Two liquid-membrane-liquid variable-focus lenses were adopted for the achromatic doublet design, and we could set the lenses dispersion by choosing the liquid candidates and manipulate the two lenses' powers by controlling the shapes of the membranes. The merit of this proposed doublet is obvious that the chromatic aberrations in a scale of focal range could be dynamically corrected as long as we control the two lenses' characters correspondingly in arrangement. The design example was given in detail: two variable-focus lenses were set as two elements with low and high dispersions according to the design principle of the traditional achromatic doublet, and the correction of the chromatic aberration in scale of focal range were confirmed by the two variable-focus lenses cooperative adjustment strategy.

9193-21, Session 5

Chords and harmonies in mixed optical and acoustical stimuli *(Invited Paper)*

Cornelius F. Hahlweg, bbw Hochschule (Germany); Cornelia Weyer, G&S Sicherheit für Betriebe GmbH (Germany); Joachim Dörfler, Ronny Fischer, bbw Hochschule (Germany)

The paper is a follow up of the work presented in last year's Optics and Music session on the perception of coherence between low frequency power modulated light and periodical acoustic stimuli. The composition of chords and harmonies from power modulated light sources and their effect as stand-alone stimulus and in conjunction with the equivalent acoustic signal is discussed. Of special interest here is the modulation right above perceptible flicker frequency. The substitution of acoustical chord components by their optical counterpart and vice versa is investigated. Further, tests on a training application for trombone players are presented: since the mean slide of the trombone does not have fixed positions, the note must be found and two players might influence each

other. The possibility of helping them to synchronize by optical stimuli derived from their playing is investigated. Beside possible applications in emotional reinforcing multi-media oriented entertainment and training support for musicians, again implications for occupational medicine are discussed.

9193-22, Session 6

Near-field imaging techniques for surface inspection

Cornelius F. Hahlweg, bbw Hochschule (Germany); Lukas Pescoller, Peret GmbH (Italy)

Following the recent work on the characterization of flexo-printing plates a device for inspection of glossy surfaces using a defined out of focus image of the surface under parallel illumination is presented, which in principle represents a near field distribution of the reflexion function of the surface. The image turns out to be equivalent to a focussed shadowgraph as used for the investigation of processes in transparent media. Beside the plain 'reflected shadow imaging' several degrees of freedom can be exploited for configuration of the feature emphasis. The method is especially interesting for the quality control of printed matter. In the paper the definition of the system, the mechanism of the imaging process and its relation to the real image of the surface itself are considered. Further questions of resolution, extractable features and extended applications are discussed.

9193-23, Session 6

Improved methods for adjusting the UV contents of standard illuminations for papermaking industry

Li Yang, Innventia AB (Sweden)

Many commercial materials (papers and boards) contain optical whitening agents (OBAs). Adequate adjustment (control or adjustment) of UV content of measurement apparatus (e.g. spectrophotometer) is essential for accurate colour measurement. In the methods described in the current ISO standards, the UV content of an instrument's illumination is adjusted against a single assigned value (total energy of part or the entire UV spectrum) of a transfer standard for fluorescent reflectance factor. For example the measurement of CIE whiteness (D65/10 o) the total UV is adjusted to match CIE illuminant D65, while for ISO Brightness the match is to the total UV content of CIE illuminant C. This approach is simple and easy to implement but suffers from potential weakness in reliability and precision. Therefore, alternative methods have been developed for adjustment of the UV content. Instead of (adjusting the UV content of an illumiant against) a single assigned value, the new methods enable one to adjust the UV content of an illuminant against assigned spectra. This is achieved by numerical filtering techniques, i.e. linear combinations of spectra obtained by employing different UV filters, primarily the UV cut-off filters at 395 nm and 420 nm, which are commonly used in an ordinary spectrophotometer. Different from the effects of the filters inside the instrument, more than unity (100%) and negative contributions (to the linear combination) are allowed. Preliminary tests have shown very promising results.

9193-24, Session 6

Concurrent multi-view discrete spectral imaging device from the VIS to the NIR

Farnoud Kazemzadeh, Shahid Haider, Alexander Wong, Christian Scharfenberger, David A. Clausi, Univ. of Waterloo (Canada)

Instruments used for multispectral and stereoscopic imaging are often large, operationally time-consuming, expensive, and are dedicated devices used in well controlled settings. A single instrument capable of performing both tasks, concurrently, in a single acquisition, has been developed. The optical design of a hand-held device which is capable of imaging multiple spectral bands as well as multiple perspective views of a field of view, in a single exposure, is presented. The device is created by making permanent augmentations to a camera. This device allows for imaging of six independent spectral bands in concert with five different perspective views of a given target, simultaneously on a single detector. This device utilizes a series of mirrors positioned obliquely to the principle axis of the imaging device that present different perspective views, of a target. The views are then simultaneously bandpass filtered and are imaged on the camera in a single exposure. The device enables spectral measurement of various targets in the visible and the near Infra-red wavelengths hence enabling multispectroscopic science. Exploiting the multi-view imaging capability of the device, depth information can be obtained and used for topological, three-dimensional surface reconstruction of a given target. Some applications of such a device are explored accompanied by demonstration of the merits of multispectral image analysis. Three-dimensional reconstruction of a few objects is also presented.

9193-25, Session 6

Zepto-mole detection in microfluidics by novel nonlinear multi-photon laser wave-mixing spectroscopy for biomedical and environmental applications

Marcel M. Hetu, Manna F. Iwabuchi, Eric Maxwell, Haoli Wu, Sashary Ramos, William G. Tong, San Diego State Univ. (United States)

Nonlinear laser wave-mixing spectroscopy is presented as an ultrasensitive detector that yields zepto-mole or parts-per-quadrillion-level detection sensitivity when interfaced to microfluidic systems, microarrays, lab-on-a-chip, capillary electrophoresis and other capillary- or fiber-based chemical separation systems. Multi-photon laser wave mixing is an absorption-based detection method for chemical and biological agents, and unlike conventional absorption detection methods, wave mixing allows detection of micrometer-thin samples at zepto-mole sensitivity levels. For biomedical and environmental samples, wave mixing offers significant advantages including excellent detection levels in microchannels and thin films, label-free detection of samples in their native form, small sample requirements, short optical path lengths, high spatial resolution and high spectral resolution. We have demonstrated ultrasensitive detection levels using a wide range of sample types including gas and liquid-phase samples, thin films and surface deposits. Unlike fluorescence-based methods, wave mixing allows the use of both fluorophores and chromophores as labels, if labels are desired, since wave mixing is an optical absorption method. Since the wave-mixing signal is a coherent laser-like beam with its own propagation direction, it can be detected efficiently against a dark background, yielding excellent S/N and virtually 100% signal collection efficiency. We have used a wide range of fixed and tunable lasers with wavelengths from UV to mid-IR (quantum cascade lasers) for detection and identification of complex biological samples when coupled to microfluidics. Neurotransmitters, biomarkers, cancer cells and environmental samples can be detected and fingerprinted using compact portable optical designs that can be battery powered and used in the field.

9193-26, Session 7

Design and characterization of a copolymer radial gradient index zoom lens

James A. Corsetti, Greg R. Schmidt, Duncan T. Moore, Univ. of Rochester (United States)

Gradient-index (GRIN) materials are ones for which the index of refraction varies as a function of spatial coordinate. Radial geometry

GRIN elements composed of a copolymer of the two monomers methyl methacrylate (MMA) and styrene have been used in the design of a number of zoom systems across the visible spectrum. The different zoom lenses studied vary in their zoom ratio as well as in the number of moving groups within the lens. For a given number of lenses, a system which includes GRIN materials is shown to offer superior imaging performance over a system composed of homogeneous glass aspheric lenses while reducing weight. This improvement in system imaging performance is due to the fact that GRIN materials offer unique dispersion characteristics that are often very helpful in the correction of axial and lateral color in an imaging system. The MMA/styrene copolymer has a GRIN Abbe number of 9 over the visible spectrum, allowing the material to function as a flint over this waveband. Using Buchdahl notation, a new macro has been written in CODE V® optical design software for the purpose of calculating the Seidel contributions to both axial and lateral color for a GRIN material. This analysis tool is presented and used to help determine the chromatic properties of the GRIN designs on an element-by-element basis.

9193-27, Session 7

Plenoptic camera image simulation for reconstruction algorithm verification

Jim Schwiegerling, College of Optical Sciences, The Univ. of Arizona (United States)

Plenoptic cameras have emerged in recent years as a technology for capturing light field data in a single snapshot. A conventional digital camera can be modified with the addition of a lenslet array to create a plenoptic camera. Two distinct camera forms have been proposed in the literature. The first has the camera image focused onto the lenslet array. The lenslet array is placed over the camera sensor such that each lenslet forms an image of the exit pupil onto the sensor. The second plenoptic form has the lenslet array relaying the image formed by the camera lens to the sensor. We have developed a raytracing package that can simulate images formed by a generalized version of the plenoptic camera. Several rays from each sensor pixel are traced backwards through the system to define a cone of rays emanating from the entrance pupil of the camera lens. Objects that lie within this cone are integrated to lead to a color and exposure level for that pixel. To speed processing three-dimensional objects are approximated as a series of planes at different depths. Repeating this process for each pixel in the sensor leads to a simulated plenoptic image on which different reconstruction algorithms can be tested.

9193-28, Session 7

Ultra-slim wafer-level camera with 720p resolution using micro-optics

Andreas Brückner, Alexander Oberdörster, Jens Dunkel, Andreas Reimann, Frank C. Wippermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The slim design of portable electronic devices (e.g. smartphones) causes a constant need for miniaturized camera systems. This trend pushes the shrinking of opto-electronic, electronic and optical components. While opto- and micro-electronics have made tremendous progress, the technology for the miniaturization of optics still struggles to keep up. The demand for a higher image resolution and large aperture of the lens (both driven by shrinking pixel size) conflict with the need for a short focal length and a simple, compact design. These conditions impose high demands on the fabrication technology, especially when considering that it has to meet one-hundreds of a percent relative accuracy. Wafer-level optics (WLO) fabrication for camera lenses is a promising candidate, enabling high-volume production with low cost. However, the resolution that is currently available with WLO-technology is limited to 1MP per lens due to material and process control issues.

We propose an alternative lens design using a multi aperture scheme which captures different portions of the field of view (FOV) within separated optical channels. The different partial images are joined digitally to reconstruct an image of the full FOV. The segmentation partly decouples the tradeoff between focal length and size of the FOV. The advantage is twofold: A short total track length is created and the microlenses are easier to manufacture. The realization of such multi aperture objectives is feasible with adapted micro-fabrication techniques such as diamond milling, step and repeat micro-imprinting and UV-molding. Alignment and assembly are partially carried out on wafer-level. The optical design, technological realization and test of such a multi aperture system is discussed for the example of a 2mm-thin camera module with 720p resolution.

9193-29, Session 7

A hyperchromatic lens for recording time-resolved phenomena

Daniel K. Frayer, Morris I. Kaufman, National Security Technologies, LLC (United States); Gene Capelle, National Security Technologies LLC (United States)

Current methods of recording multiple-frame images at short time scales are limited by electro-optic tube physics and radiometry. A new all-optical methodology has been developed for the capture of a high number of quasi-continuous effective frames of 2-D data at very short time scales, with improvement over existing framing camera technology in terms of short recording windows and effective number of frames. The methodology combines active illumination in which wavelength is dependent upon time and spatial position to encode temporal phenomena onto wavelength; a strong hyperchromatic lens to map wavelength onto axial position; and a recording technology, such as holography or plenoptic imaging, to capture the resultant focal stack in both spatial (imaging) and longitudinal (temporal) axes. The novel hyperchromatic lens we designed incorporates a combination of diffractive and refractive components to maximally separate focal position as a function of wavelength, resulting in a 50 mm focal stack with nearly constant magnification for just 5 nm of illumination light. The fabricated lens assembly was qualified as meeting design requirements and images with the expected magnification at nearly the diffraction limit across the spectral range. Criteria for incident illumination and focal stack recording and potential methodologies for achieving them are described. Potential uses and limitations for this technology are also suggested.

9193-30, Session 7

Freeform mirror for illumination system of color-sequential LCOS pico projector

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An efficient and uniform illumination system with a freeform mirror for a color-sequential LCOS pico projector based on LED is proposed. The illumination system comprises LED, collimators, a homogenizer and a LCOS panel. Collimators add on LED to provide near parallel light with low numeric aperture divergent angle. Lens array architecture with benefit of shorter optical path length is chosen to convert Gaussian-like irradiance from collimators into uniform irradiance. The typical design for lens array is the length-to-width ratio of lenslet corresponding with the ratio of the panel. However, the crosstalk phenomenon occurs due to lens array with different collecting angle in horizontal and vertical direction, especially on 16:9 panel. The crosstalk phenomenon not only reduces the illumination efficiency but also generates stray light on the panel, so we use a lens array with square lenslet to eliminate it. The square light pattern on the panel needs to be reshaped to fit 16:9 panel. A cylinder mirror with a fixed power can be used to compress the light pattern. Because of the requirement of different focal distance from cylinder mirror to panel on entire surface, it generates severe keystone phenomenon. A freeform mirror with progressive power variation is employed to correct keystone for high overfilled efficiency and reshapes

the light pattern fitting the ratio of the panel. The uniformity of JBMA on panel is above 95% and coupling efficiency from LED to the plane of panel is 85 %. The illumination system with high brightness, good uniformity and low stray light is developed. Furthermore, the alignment tolerance of freeform mirror is also discussed. Finally, the freeform mirror is fabricated by ultra-precision diamond milling method. The form accuracy and surface roughness of the freeform mirror are less than 0.5 um and 5 nm, respectively.

9193-31, Session 7

Image exposure suppressed optical system by spatial light modulator

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Most of the conventional CCD and CMOS sensors in the market possess lower dynamic range compared to human eyes. The limitation on the dynamic range often results in over-exposure on the final image. In this work, we present a novel optical design to overcome the over-exposure problem without increasing the specifications of sensors. A spatial light modulator (SLM), which is commonly used for modulating light intensity, is used in our design. In projector systems, DMD and LCoS are commonly used in modulate the intensity of the projected images. In our design, reverse of this design concept is employed. Intensity modulation is performed on object space, instead of image space. Our design consists of two optical systems. The first system images the object onto the SLM, which will modulate the light intensity to prevent over-exposure. The second system then relays these modulated images onto CCD or CMOS sensors. Our design has successfully reduced over-exposure problems and produced clear images using conventional optical sensors.

9193-40, Session PMon

WDM-PON Network Simulation with Different Implementation of Optical Amplifier in the Line

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This article is dealing with simulation of different types of optical amplifiers utilized at various positions (as a preamplifier, in-line amplifier or output amplifier) in WDM-PON network line. The bit rates of 125 Mbps, 1.25 Gbps, 2.5 Gbps per channel that are easily attainable were taken into account in simulation. Implementation of optical amplifiers at different spots then has different influence on possible achievable distance of WDM-PON network. For the simulated topologies were observed parameters of bit error ratio, attenuation, Q-factor, optical signal to noise ratio, etc. The whole designed WDM-PON network topology was based on commercially available device LG-Ericsson EAST 1100. From the real measurements and available datasheets were obtained necessary simulation input parameters so that all simulated data were utmost corresponding to the real measured results.

9193-42, Session PMon

A new method of grating fabrication by using auxiliary grating

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Gratings are key elements of spectroscopy instruments because of small aberrations and high resolution. In the production of gratings, Lloyd mirror optical path is widely used. Usually, spherical waves reflected by the Lloyd mirror and the original spherical waves interfere with each other on the grating substrate coated with photoresist. The photoresist is exposed and developed to form the grating mask. However, such a grating having a linear density deviation from the spherical wave. For the grating with large size, this kind of deviation can not be negligible. In order to produce gratings with more precise line density, a new method is introduced. The plane wave, which come from the spherical wave diffracted by auxiliary grating, is irradiated onto the Lloyd mirror. The plane wave reflected by the mirror and the original plane wave interfere with each other. There are three major contributions in this paper. Firstly, parameters of auxiliary gratings are optimized based on the theory of ray tracing and genetic algorithms. Secondly, the experimental optical path is given and the lines density of grating is measured via autocollimation methods. Finally, linear density is compared between gratings produced by the plane and spherical waves. The results demonstrate that gratings fabricated by using auxiliary gratings having more precise linear density, especially for large-sized gratings.

9193-44, Session PMon

High-speed phosphor-LED wireless communication system utilizing no blue filter

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In this investigation, we first propose and demonstrate an adaptively 84.44 to 190 Mbit/s phosphor-LED visible light communication (VLC) system under practical transmission distance. Here, we use the orthogonal-frequency-division-multiplexing quadrature-amplitude-modulation (OFDM-QAM) modulation with bit-loading algorithm in VLC system. In this experiment, the optimal analogy pre-equalization design is also performed at LED-Tx side and no blue filter is used at the Rx side for extending the modulation bandwidth from 1 MHz to 30 MHz. Moreover, the corresponding free space transmission lengths are between 0.75 and 2 m under various traffic rates of VLC system. And the measured bit error rates (BERs) of < 3.8e-3 [forward error correction (FEC) threshold] at different transmission distances and measured data rates can be also obtained.

Furthermore, in European Union Project OMEGA, an indoor VLC link including a MAC layer protocol adapted to optical wireless communications systems was demonstrated. It operated at 84.44 Mb/s and was successfully used to transmit three high definition video streams. Recently, HHI demonstrated few hundreds Mb/s VLC systems within a room scale. We believe that our proposed scheme could be another alternative VLC implementation in practical distance, supporting > 100 Mb/s, using commercially available LED and PD (without blue filtering) and compact size.

9193-45, Session PMon

Coherent-light-based optomechanical door locking system

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We present Coherent Light based Optomechanical Door Locking System (CLOD- Locking System), an optical system that combines a simple combination of a coherent light source (Laser) and a photodiode based sensor with focus toward security applications. The basic construct of the key comprises a Laser source in a cylindrical enclosure that slides perfectly into the lock. The Laser is pulsed at a fixed encrypted frequency unique to that locking system. Transistor-transistor logic (TTL) circuitry is used to achieve encryption. The casing of the key is designed in such a way that it will power the pulsing laser only when the key is inserted

in the slot provided for it. The Lock consists of a photo-sensor that is perfectly aligned with the pulsed laser. The function of the sensor is to convert the detected light intensity to a corresponding electrical signal by decrypting the frequency. The lock also consists of a circuit with a feedback system that will carry the digital information regarding the encryption frequency code. The information received from the sensor is matched with the stored code- If perfectly matched, a signal will be sent to the servo to unlock the mechanical lock or to carry out any other operation. This system can be used in security systems for residences and safe houses, and can easily replace all conventional locks which employ fixed patterns to unlock. The major advantage of this system over the conventional systems is that other systems which rely on a fixed pattern to perform its task, can be easily hacked or tamper with. . The proposed system does not consist of any such kind of solid/imprinted pattern and hence makes it almost impossible to tamper with.

9193-46, Session PMon

Modeling large deflection of circular membranes for applications in active optical elements

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The field of active optical elements with variable parameters is rapidly developing nowadays. Various optoelectronic elements based on different physical principles such as deformable mirrors, variable focus lenses, liquid crystal spatial light modulators are being investigated and implemented in optical systems in recent years. One possibility of practical realization of an active optical element that can change the parameters of the transmitted or reflected wavefield is the use of a pressure actuated membrane as an optical surface of a given element. The shape of this membrane is controlled by a pressure of a liquid or gas in the chamber behind the membrane surface. This principle can be used both for construction of the deformable mirror, and for construction of the liquid membrane lens with tunable focal length, in which case the membrane has to be made of optically transparent material. Our work is focused on a theoretical description and mathematical modeling of the shape of the circular edge clamped pressure actuated elastic membrane, which can be used as an optical surface of such an active optical element. While the theory of small deformations of elastic plates and membranes is well developed and the calculation of a deflection of the membrane can be done with a relatively good accuracy, modeling of large membrane deflections is more complicated. Classical approaches given in literature adopt certain approximations that affect the accuracy of the calculated shape of a membrane. In our work a generalized nonlinear differential equation describing a given problem is derived and the method for solving this equation is proposed. The numerical solution is based on the expansion of the solution into series and transformation of the problem into the constraint optimization problem. It is shown on examples that the deviation of the shape calculated using the proposed generalized equation and the classical solution is not negligible in terms of the requirements on optical surface accuracy. The influence of membrane shape on optical quality and design of membrane fluidic lenses is also investigated.

9193-47, Session PMon

Radiation-tolerant camera system to provide inspections inside nuclear power plant reactors

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The radiation-tolerant camera system is the part the power plant equipment to increase plant safety and efficiency through the use of technology advancements. It provides the system linear dimensions measurements in the harsh environments: inside the nuclear power plant reactor in case defects are found. It includes CCD-camera that is fitted with guidance, high-intensity LED lighting, processing system and user interface. The camera offers the perfect mix of high resolution, small size, and high radiation tolerance. Due to its compact diameter the camera is perfectly suited for inspection of confined areas and in reactor components. The LED lightning device meets the same environmental and high-radiation specifications as the camera itself and provides the illumination of the inspection area.

The paper is devoted to the specifics of the design of camera and illumination device, estimation of the resolution of the system described above.

9193-48, Session PMon

Transformation optics with windows

Stephen Oxburgh, Christopher D. White, Georgios Antoniou, Ejovbokoghene Orife, Johannes Courtial, Univ. of Glasgow (United Kingdom)

Transformation optics is a new design paradigm that allows the design of metamaterial structures that behave, to light, like curved spaces. The headline application, invisibility cloaking, has created much interest with scientists and the public alike.

Transformation-optics devices built from metamaterials have many limitations, for example the very high cost of creating even tiny volumes of the nano-structured materials required for operation in the visible wavelength range, and the very narrow wavelength band over which metamaterials have the desired properties.

Pairs of microlens arrays that are separated by the sum of their focal lengths form arrays of micro-telescopes. Such arrays are pixellated windows (each telescope is one pixel) that change, over a limited field of view but also over a wide wavelength range, the light-ray direction of transmitted light rays like the interface between different materials. In principle, they can also be manufactured cheaply and in bulk. By exploiting the fact that these windows are (in principle) perfectly imaging [S. Oxburgh and J. Courtial, J. Opt. Soc. Am. A 30, 2334 (2013)], we demonstrate that such windows, when combined into suitable structures, are pixellated transformation-optics devices. This new class of transformation-optics device can be macroscopic in size, and so such devices offer a very different compromise to metamaterial transformation-optics devices. This should significantly widen the applicability of transformation optics.

9193-49, Session PMon

Non-absorbing metamaterial film with dispersion of effective refractive index

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Thin-film single- or multilayer interference coatings are commonly employed for manufacturing highly transparent low-reflective optical systems operating in a wide spectrum range. However, their application is essentially constrained by a necessity to use bulk films of the given thickness made from diverse substances. Another way to achieve the minimum reflection in a given spectrum range, thereby providing a wide-range antireflection, is to use materials with the frequency dispersion of the refractive index. We have studied the optical properties of dielectric films with embedded quasicrystal layer of nanosize objects (nanocavities of various shape). The considered system is shown to exhibit the refractive index frequency dispersion, zero absorption and is able to vary

the effective optical thickness with the light wavelength. The obtained result does not contradict the Kramers-Kronig relation that originates from the causality principle and requires non-zero imaginary part of the dielectric permittivity in case of real part dispersion. The dispersion of the effective refractive index of a film is determined by the character of light scattering by nanosize objects as well as by cooperative effects in ordered nanostructure and could not be achieved in a bulk film or in a film with chaotically distributed nanosize objects of diverse shape. The obtained structure could be employed as a wide-band single-layer antireflection coating, for it satisfies (at least partially) condition of maximum transmission not at a definite wavelength only, but within some spectral range.

9193-50, Session PMon

A pair of diopter-adjustable eyeglasses for presbyopia correction

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An ophthalmological application of presbyopia eyeglasses with a variable-focus lens was discussed. Nowadays there is a huge population of old people who do not receive appropriate treatments and this number is in a rapidly increasing tendency due to the aging society and the low-birth rate. Because of losing elasticity of crystals lens and power of ciliary muscle, the accommodation of presbyopia patients' eye results into a special character. They need different diopters to observe the objects in different distances. The exiting treatments cannot provide a perfect correction, such as the wavy distortion of the bifocals, and some of them even cause dizziness and headaches.

We proposed a pair of diopter adjustable glasses by using two variable-focus lenses with liquid-membrane-liquid structure. A tunable diopter covered the whole lens cell, so the users would enjoy a whole vision zone and there is no wavy distortion. To friendly adjust the lens diopter, a touch roller ball had been embedded on the bridge of the glasses and it could sense the touching gesture to gradually increase/decrease liquid volume inside of the lens, in turn gradually control its diopter. A principle experiment was conducted and the presbyopia's vision was mimicked by a digital camera, and the results showed that presbyopia patients could clearly observe the near objects under the assistant accommodation of the glasses. The proposed prototype is a bulky size in the lab, but according to the calculation of the control requirements, it is very possible to be designed into a wearable size.

9193-51, Session PMon

Fabrication of wide-infrared spectral disperser of ZnS

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We present fabrication and tests of ultra-wideband infrared spectral disperser of ZnS, of which the primary application platform is space-borne infrared astronomical telescopes for measurement of atmospheric composition of transiting exoplanets. The wideband coverage, 1-13 micron wavelength region, is realized by cross-dispersion of ZnS prism and grating fabricated on a surface of the prism.

Advantages of spectrometer using this disperser are being compact and simple, having high efficiency and stability. Therefore, such spectrometer is quite suitable for the use for the observation of exoplanet atmosphere by monitoring observation with a space infrared telescope. We carried out examinations of the fabricated ZnS disperser in the air at ambient temperature. Results of tests of the fabricated disperser satisfied requirements: We examined the pitch and blaze angle of grating pattern using a non-contact 1-D scanning measurement. As the results, the pitch of 166.7 nm rms and the blaze angle of 2.11 degree were obtained. Surface figure and roughness were evaluated using interferometers, and then the surface figure of 70 nm rms and the furface roughness of ~10 nm rms were obtained. We also present a new design of a disperser made of CdTe, which covers 1-30 micron wavelength region simultaneously.

9193-52, Session PMon

Quality improvement of transmission images for transparent displays with micro-lens array

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The electrowetting technology is the most important method for the traditional displays that can work more efficiently. When the voltage drives, the aperture ratio of the ink will reach 75% and the transmittance can reach 60%. Furthermore, the electrowetting technology has the advantages such as high transmittance, high switching speed, color performance, low power consumption, and etc. They make the advances of technology development for the transparent displays. However, due to the diffraction phenomenon resulted from periodic pixel structures, when the users observe the background object through the transparent display, the transmitted image will be blurred. In this paper, the first step is construct the optical model, and there is about 3% error of light intensity between our experiments and simulations because of some random small ink spots. In the next step, we propose a method that we utilize a pair of micro-lens array and change the different optical structures to reduce or eliminate the diffraction effect for the optical performance improvement of transmitted images of transparent displays. We insert the pair micro-lens array in two different ways. After optimizing the diameter lens array and the optical structure, the best result is that the width of diffraction reduces by 92%. Therefore, micro-lens array can reduce the diffraction effect for electrowetting display. We will use this concept for other transparent displays in the future.

9193-53, Session PMon

Simulation of integrated optical network (IPON) properties

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Nowadays, there is an increasing pressure on the efficient use of existing ICT infrastructure in order to provide the latest services for corporate customers or end users. With the increasing number of demands on services, requirements on optical networks of all hierarchy types are increasing as well. This increase in the requirements, however, involves risks which must be faced by Internet service providers. These include the maximum use of spectral range, bandwidth and reachable distance, suppression of dispersion effect, route planning efficiency, CAPEX and OPEX costs management, or successful combination of technologies of deployed networks. The aim of this article is to present the problems associated with interconnection of WDM-PON and ver.2 EPON (IEEE 802.3ah standard). The entire simulation is based on real parameters, which were provided by the manufacturers of the technologies and then measured in the laboratory. Then we were able to perform simulations based on more realistic features of these technologies.

9193-54, Session PMon

Lorentz-transformation windows

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We study windows that consist of arrays of identical micro-telescopes. Provided a light ray enters and exits through lenses that belong to the same micro-telescope (which is the case only within a finite field of view), such windows change light-ray direction independent of where a light ray hits the sheet. We have previously calculated this light-ray direction change.

Here we find that, for a specific subset of such windows which we call Lorentz-transformation windows, this light-ray-direction change distorts the scene seen through such a window in the same way in which the scene would be distorted in a photo of the scene taken with a camera moving at low, but relativistic, speed.

The latter distortion can be calculated by considering the coordinates of two “events” on the trajectory of a light pulse, i.e. two positions on the trajectory of the pulse and the times when it passed through those positions, in two frames: the frame in which the camera is at rest, and the frame in which the scene is at rest. Corresponding events in different inertial frames are related through a Lorentz transformation.

Lorentz-transformation windows can also undo the distortion of the scene when moving at low relativistic speed relative to it. They could therefore be a useful extra for future space ships moving at such speeds.

We illustrate our findings with ray-tracing simulations.

9193-55, Session PMon

Accuracy of time interval measurements by digital photochronographic system

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Curently there was developed based on rotating mirror camera digital photochronographic system, with recording information on CCD-matrix, which allows investigating high speed processes. There was analyzed measurement scheme of the digital system, and there was determine the accuracy of electrical devises and the accuracy of processing received images.

9193-56, Session PMon

Speckle reduction in projection display by controlling the spatial coherence of laser source

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In this paper, the relationship between the spatial coherence of light field and the speckle contrast in a laser based projection display system is studied under the consideration of human visual percept. By using a varifocal liquid-crystal lens and a monochromatic CCD, a system which is used for simulating the human eye is set up to record the speckle pattern. An efficient method for controlling the spatial coherence by using a dielectric elastomer actuator (DEA) is proposed. The results show that the total efficiency for energy utilization is more than 60% during our experiment. When the distance between the observer and the screen is large enough (>3 meters), the speckle contrast can be eliminated well at last (<4%) and the observer won’t feel the speckle phenomenon.

9193-32, Session 8

Unidirectional emission from whispering gallery modes via transformation optics

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It is well known from transformation optics that a light pathway can be designed with artificial materials. When a coordinate transform technique is applied to optically resonating dielectric structures, interesting phenomena can be observed as well. Generally, a long-lived whispering gallery mode (WGM) has no preferential direction of radiation because of its rotationally symmetric structure. However, if the space inside the resonator is transformed so that the discontinuity of coordinates exists, it becomes possible to reconcile directional emission with WGMs. Here, we transform only the inner space of a deformed optical cavity, e.g., the Limaçon cavity into a virtual perfect disk via a conformal mapping and show these two seemingly incompatible behaviors can be observed simultaneously. The refractive index profiles that realize the transformed space can be obtained from the conformal space transformation.
The resonant mode calculated with a transformed boundary element method shows that the WGMs can restored for the deformed cavity. The Husimi function calculated for this transformed cavity shows a weighted band-like profile, which implies that the optical rays inside the cavity is maintaining its reflecting angle as is for the original cavity. However, the far-field pattern shows anisotropic emission of radiation because it is determined by tunneling through the rotationally asymmetric boundary. For example, the conformal WGMs in Limaçon and center-shifted triangular cavities exhibit bi-directional and uni-directional emission patterns in the far-field, respectively. This conformal WGM cavities with both the ultra-high quality factor and the directional light emission may be used in the realization of efficient directional light sources.

9193-33, Session 8

Reduced group delay dispersion in quantum dot passively mode-locked lasers operating at elevated temperature

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Quantum dot (QD) passively mode-locked lasers (MLLs) have emerged as a leading source for efficient generation of high quality optical pulses from a compact package. Characteristics such as low noise operation, high pulse peak power and scalable pulse repetition rates from the hundreds of GHz to potentially 1 THz, have garnered considerable attention for support of multiple high-speed applications [1,2]. This paper will address the optimization of the QD MLL pulse characteristics when operating at elevated temperature.

While traditionally, the time-domain pulse characteristics of semiconductor MLLs have been studied using digital sampling oscilloscope or intensity autocorrelation techniques, it has been shown that simultaneous characterization of time and frequency is necessary and sufficient for true determination of mode-locked stability [3,4]. We have performed state-of-the-art Frequency Resolved Optical Gating (FROG) pulse measurements on a two-section passive QD MLL over wide temperature excursions. This unique measurement allows for extraction of the temporal and spectral intensity and phase profiles, from which the Group Delay Dispersion (GDD) can be determined. The magnitude of the GDD is found to decrease from 16.1 to 3.5 ps/nm when the temperature is increased from 20 to 50 C, mirroring the trend of pulse width reduction at elevated temperature, which has been shown to correlate strongly with reduced unsaturated absorption [5]. The possibility to further optimize pulse generation via intra-cavity dispersion compensation in a novel three-section MLL design is also examined, and shows strong potential toward providing valuable insight into the optimal cavity designs and operating parameters for QD MLLs.

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9193-34, Session 8

Reaction bonded silicon carbide material characteristics as related to its use in high power laser systems

Matthew Pitschman, Travis S. Miller, Alan R. Hedges, Steve P. Rummel, II-VI Infrared (United States)

Reaction bonded silicon carbide is a durable material that is well suited for use as high power laser mirror substrates. The reaction bonded material (RBSC) has a low mass density, high Young's Modulus, good thermal conductivity, and very low coefficient of thermal expansion. All of these properties are beneficial in mirror substrates used in multi-kilowatt lasers. In conjunction with the development of the mirror material, special polishing processes, fabrication processes, and coatings have also been developed. In this paper we will present a comparison of material properties of SSC and other mirror materials currently used in high power lasers. A brief overview of the critical fabrication and coating processes will also be reviewed. Finally, we will present thermal heat load test data showing the surface deformation of various high power mirrors used under heat loads typically found in laser systems operating at average powers greater than 10 kilowatts.

9193-35, Session 8

The new design of final optics assembly on SG-III prototype facility

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The SG-? prototype facility (TIL) is a flash-lamp pumped Nd:glass laser system that functions as a scientific prototype of an advanced inertial fusion laser. The final optics assemblies (FOAs) of TIL, that mount on the target chamber, convert the amplified 1.053 um beams from the Nd:glass driver to the third harmonic and focus them onto the target. With the final optics in FOA, it combines a number of functions: frequency conversion, focusing, color separation, diagnostic beam sampling, vacuum isolation and debris shielding. The optics after frequency conversion are made of fused silica (SiO_2), which are the most exposed to laser damage, due to higher energy photons of the tripled frequency (3?) and downstream of the optical path. The surface damage is a major concern and a potential threat for optics operational lifetime. Thus it is crucial for integratedly optimizing FOA that meets the multi-functions and extends the lifetime of final optics.

To improve the performance of TIL, FOA is re-designed. It contains that stray light and focusing ghosts are optimized, operational performance and environments are improved and the total thickness of optics is reduced. With the re-designed FOA, Some performance advantages are achieved. First, the optics damages are mitigated obviously, especially crystals and Focus lens; Second, stray light and focusing ghosts are controlled better that organic contamination sources inside FOA are eliminated; Third, maintenance and operation are more convenient for the atoms environment; Fourth, the focusable power on target is increased for lower B-integral.

9193-36, Session 8

The performance of the disk amplifier system in the integration test bed

Lin Chen, LFRC (China)

The experimental results of the new designed single segment disk amplifier with 400mm aperture in the Integration Test Bed(ITB) were introduced. The bank-to-lamp transfer efficiency reached 92% due to special designed. The average small signal gain coefficient reached 5.28%/cm with the gain uniformity (maximum/average)was 1.06:1. The energy storage efficiency was 1.62%. The Pump-Induced-Distortion of the laser chain was 5.3? and in the correct range of the deformable mirror.The recovery of the amplifier was less than 4 hours.With the multi-pass amplifying structure,the laser output of 1053nm reached 19.6kJ/5ns.

9193-37, Session 9

Impact of green technologies in optical networks case study: green wireless optical broadband access network

William S. Puche, Univ. Pontificia Bolivariana (Colombia) and Politécnico Colombiano Jaime Isaza Cadavid (Colombia); Javier E. Sierra, Univ. Pontificia Bolivariana (Colombia)

This article provides an analysis of the current state of green technologies in optical telecom networks. Initially discusses the basic structure of a telecom network, considering the energy consumption of the equipment within it, includes a mathematical model to found the optimal number of active ONUs in a WOBAN network, next to it a study of energy-efficient technological developments made by research centers and corporation is also presented and finally the benefits and disadvantages of the implementation of the technologies discussed are analyzed.

9193-38, Session 9

Design of visible light communication system for maintaining uniform data rate

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Light-emitting diode (LED) is gradually replacing the fluorescent lamp for lighting. Higher modulation bandwidth of LEDs makes the additional application of visible light communication (VLC) possible. Every location of a VLC system should be provided by equal data rate for justice consideration. However, locations away from the LED lamp have less power. These low-power locations have lower signal-to-noise ratio (SNR); and hence lower data rate can be achieved. For achieving high capacity VLC, strategies should be adequately provided to mitigate this problem.

In this paper, a strategy was proposed to solve the above problem. SNR distribution of the VLC system is designed to ensure uniform data rate. Discrete multi-tone (DMT) is used for this VLC system. The DMT subcarriers are bit-loaded depending on the LED frequency response. More subcarriers are allocated for communication at low SNR locations. Hence, nearly equal data rate can be provided everywhere. Because each location within this VLC system is communicating using different subcarriers, real-time continuous applications, such as video and voice, can be carried out. Demonstration of 13.6 Mb/s data rate was provided.

9193-39, Session 9

Data transmission with OFDM technique using soliton carriers

Kamaljit Singh Bhatia, Taranveer Kaur, Sri Guru Granth Sahib World Univ. (India)

OFDM provides both high data rate and symbol duration with overlapping sub carriers without causing inter carrier interference using frequency division multiplexing (FDM) over multi sub carriers within one channel. Besides that solitons pulses retain their shape over a long distance so providing good transmission rate over long distance. To best utilize the available bandwidth in optical channel, multiuser structures of soliton pulses with proper adjustment of the initial laser phase values at different transmitter , plays efficacious role on the performance (in terms of Q-values, jitter and BER at the receiver) of the transmission . Besides that jitter is an effect that results in undesirable causes in the system , hence very important to be minimized. We proposed a new system (as shown in conceptual diagram) for transmission of data with orthogonal frequency division multiplexing technique for communication network using solitons as carriers with minimized jitter. Here multiple soliton carriers are multiplexed and modulated using an OFDM technique. It will result in boosting capacity of data transmission over long range communication systems with improved speed and effective Peak-to average power ratio (PAPR).

Conceptual diagram of Soliton based Back-to-back OFDM transmission

photon.

9194-1, Session 1

Vector beams *(Invited Paper)*

Giovanni Milione, The City College of New York (United States)

Vector beams are light beams possessing spatially inhomogeneous, i.e., vector, states of polarization such as radial and azimuthal polarization. Due to their complex polarization vector beams can extend light's properties beyond more conventional Gaussian beams. In this talk I will give an overview of recent theoretical and experimental advances of vector beams. This will include the relationship of vector beams to light's angular momentum and so-called "classical entanglement," their application in determining orientations of single nitrogen vacancy centers in diamond, and their application to increase information capacity in optical fiber and free space communication in the classical and quantum regimes.

9194-2, Session 1

Cross-correlation measurements and the topological charge of a Laguerre-Gaussian beam

Benjamin Perez-Garcia, Tecnológico de Monterrey (Mexico); Dorilian Lopez-Mago, ETH Zürich (Switzerland); Hipolito Garcia-Gracia, Jorge A. Garza, Raul I. Hernandez-Aranda, Julio C. Gutiérrez-Vega, Tecnológico de Monterrey (Mexico)

We study both theoretically and experimentally the cross-correlation function of a Laguerre-Gaussian (LG) beam, this technique allows the determination of the topological charge of the beam by performing power measurements only. We employ a superposition of two exact copies of the original LG beam whose centroids are displaced from each other. The behavior of the auto-correlation is studied as a function of the displacement between these two copies of the beam, this is done for different topological charges. Our results indicate that the auto-correlation is described by a polynomial function of the displacement parameter, and the number of zeros of this polynomial maintains a one to one correspondence with the topological charge. A detailed description of the experiment to perform these measurements is also provided, our experimental findings are in excellent agreement with the theory. This technique offers an alternative for measuring the content of orbital angular momentum in a beam without the need of a camera.

9194-3, Session 1

Self-reconstruction of radial and azimuthal polarized Bessel beams

Giovanni Milione, The City College of New York (United States)

Bessel beams are light beams with conical wavefronts; all the light's rays lie on the surface of a cone. Unlike more conventional Gaussian beams with plane wavefronts Bessel beams exhibit the ability to self-reconstruct, i.e., their intensity seemingly "heals" upon propagation through an obstruction. In this talk, we will show vector Bessel beams, e.g., Bessel beams with radial or azimuthal states of polarization, can remarkably exhibit the ability to self-reconstruct their complex polarization in addition to their intensity upon propagation through an obstruction. The potential application of this 'polarization self-reconstruction' in optical trapping and quantum entanglement will be discussed.

9194-4, Session 1

Generating non-diffracting electron Bessel beams by nanofabricated pure-phase holograms

Ebrahim Karimi, Univ. of Ottawa (Canada); Vincenzo Grillo, Consiglio Nazionale delle Ricerche (Italy)

Generating electron beams possessing specific wavepackets recently receives immense applications. In particular, two different approaches for generating free electron wavepackets with a helical wavefront have been proposed and examined experimentally. These beams carry a well-defined value of orbital angular momentum (OAM) potentially suitable for material science studies. Each electron having such a wave-packet possesses an intrinsic OAM, up to several hundred $hbar$, which results in a "novel" Bohr magneton - different from the spin ones. In my talk, I review our recent achievement on fabricating the first nano-scale pure phase hologram (known as a kinoform in optics) for electron beams. Indeed, generating a kinoform for an electron beam requires a precise control of atomic well-potential in the membranes that can introduce a desired "optical path" to the transmitted electrons. This nano-scale kinoform, does not absorb electrons - nevertheless alters the "phase" of the electron. Thus, it leads to a much more efficient beam shaping devices for electron beams. We implemented this technique and manufactured particular kinoforms for generating electron Bessel beams of different orders. The first non-diffracting electron Bessel beam is, then, observed experimentally. We have also verified their diffraction-free feature by recording the probability distribution of electron Bessel beam in the transverse plane upon the propagation.

9194-5, Session 1

Optical information transfer based on helico-conical laser beams

Mona Mihailescu, Univ. Politehnica of Bucharest (Romania); Cristian Kusko, National Institute for Research and Development in Microtechnologies (Romania); Liliana Preda, Univ. Politehnica of Bucharest (Romania)

Optical beams with different spatial intensity distributions containing modulated phase are interesting in many applications including coherent optical communication, photolithography, laser processing, optical tweezers, microscopy, optical data storage. The potential of beams with peculiar controlled spatial intensity and phase distribution is exploited in the optical information transfer process. In this context, in recent years, optical vortices are used to combine informations from multiple sources using these distinct spatial intensity distributions as individual channels — a technique known as spatial-division multiplexing. Their combination with another phase distribution is not enough exploited yet, although this offers more degrees of freedom.

In this study, we started with holographic masks (HMs) generation using the classical method based on the simulation of the interference phenomenon between a reference beam and a signal beam, which passes through the object. We investigate different combinations (sum, product, hybrid) between conical and helical phase distributions to obtain compose objects. Their constructive parameters are contained in the generated HMs and these informations are transferred in the diffraction pattern. We explored experimentally the dynamics of the diffracted intensity, in two and three dimensions, when these HMs are addressed onto programmable spatial light modulator. The diffracted intensity patterns exhibit asymmetric shapes and peaks along the optical axis in all analyzed compound objects. To find the constructive parameters used in the HMs generation, based only on the spatial distribution in the final diffracted pattern, we introduce a reading mask in the optical path. The generation of these reading masks in each case is discussed.

9194-6, Session 2

Generation and detection of Laguerre-Gauss modes using a phase-only spatial light modulator and an application to quantum computations *(Invited Paper)*

Ebrahim Karimi, Univ. of Ottawa (Canada)

In addition to the spin degree of freedom, light can also have the so-called transverse degrees of freedom. These degrees of freedom are associated with the azimuthal and radial indices, l and p, which characterize a Laguerre-Gauss mode. The Hilbert subspaces associated with these transverse degrees of freedom are unbounded, and thus provide a potent environment for a variety of experimental quantum applications such as dense-coding, quantum key distribution and cloud computations. It is therefore highly desirable to acquire means of generation and detection of photonic Laguerre-Gauss modes. In this talk, I will review a very recent approach to generate and detect transverse photonic states by means of only-phase spatial light modulator and its applications to examine quantum tests.

9194-7, Session 2

Simulating spontaneous parametric down-conversion using classical light

Yingwen Zhang, CSIR National Laser Ctr. (South Africa); Melanie Mclaren, CSIR (South Africa); Filippus S. Roux, Andrew Forbes, CSIR National Laser Ctr. (South Africa)

In recent years there has been much interest in investigating photonic states entangled in orbital angular momentum due to its infinite dimensional nature. Such entangled photons can be readily generated through the process of spontaneous parametric down-conversion (SPDC), and by using spatial light modulators (SLM) one can select the mode which is to be detected. However such a system is very difficult to setup due to the low coincidence photon count rates causing the system to be extremely sensitive to alignment of optics and the hologram used on the SLMs. We present a simple way of simulating such a system using classical light and two SLMs through a back projection setup. This system has the advantage of having very high photon count rates, it can simulate a large range of pump beam profiles simply by modifying the hologram on the SLM and it can be easily converted to a SPDC setup by simply changing only two of its components without the need to perform realignment. This setup can be used to give an indication whether a SPDC experiment will be feasible in a very short amount of time.

9194-8, Session 2

Entangled Bessel beams

Melanie McLaren, Thandeka Mhlanga, CSIR National Laser Ctr. (South Africa); Miles Padgett, U. Glasgow (United Kingdom); Stef Roux, Andrew Forbes, CSIR National Laser Ctr. (South Africa)

No Abstract Available

9194-9, Session 2

Digital spiral imaging of single photons

Thandeka I Mhlanga, CSIR National Laser Ctr. (South Africa) and University of Kwazulu-Natal (South Africa); Melanie McLaren, Alpha Ibrahim, CSIR National Laser Ctr. (South Africa); Thomas Konrad, University of Kwazulu-Natal (South Africa); Andrew Forbes, CSIR National Laser Ctr. (South Africa) and University of Kwazulu-Natal (South Africa)

No Abstract Available

9194-10, Session 3

Detecting Bessel beams

Abderrahmen Trichili, SUP'COM (Tunisia) and Univ of Carthage (Tunisia); Thandeka I. Mhlanga, CSIR National Laser Ctr. (South Africa) and Univ. of KwaZulu-Natal (South Africa); Mourad Zghal, Univ. of Carthage (Tunisia); Andrew Forbes, CSIR National Laser Ctr. (South Africa) and Univ. of KwaZulu-Natal (South Africa)

Bessel beams are a non-diffractive solution of the Helmholtz equation that carry an infinite amount of energy. Bessel beams are also able, under free propagation, to reconstruct themselves after being distorted by an obstruction. Bessel Beams have a wide range of applications such as biomedical imaging, material processing, particle trapping, laser-based acceleration of particles and free space telecommunications. Experimentally, it is not possible to create an ideal Bessel Beam and so an approximation is made in the form of a Bessel function enveloped by a Gaussian profile, thereby limiting the energy carried by the field to some finite value and the generated beam is called Bessel Gaussian (BG) beam.

In this context, we demonstrate a method to generate BG beams, using digital holograms, and we perform complete modal decomposition of an optical field. Knowing that each BG beam is characterized by an azimuthal mode index l and a radial component k_r, we achieve the modal decomposition of azimuthal and radial components, with a radial spacing of 6250 m^(-1).

From the measured decomposition, we show reconstruction of the BG modes with high degree of accuracy. In order to illustrate the self-reconstruction feature of the Bessel Beam, we execute modal decomposition of an optical field after encountering an obstruction. Our results showed a fully reconstructed beam after the shadow region of the used obstruction.

9194-11, Session 3

Wavefront sensing with all-digital Stokes measurements

Angela Dudley, CSIR National Laser Ctr. (South Africa); Giovanni Milione, Robert R. Alfano, The City College of New York (United States); Andrew Forbes, CSIR National Laser Ctr. (South Africa)

A long-standing question in optics has been to efficiently measure the phase (or wavefront) of an optical field. This has led to numerous publications and commercial devices such as phase shift interferometry, wavefront reconstruction via modal decomposition and Shack-Hartmann wavefront sensors. In this work we develop a new technique to extract the phase which in contrast to previously mentioned methods is based on polarization (or Stokes) measurements. We outline a simple, all-digital approach using only a spatial light modulator and a polarization grating to exploit the amplitude and phase relationship between the orthogonal states of polarization to determine the phase of an optical field. We implement this technique to reconstruct the phase of static and propagating optical vortices.

9194-12, Session 3

Coherent radiation enhancement for laser beam shaping applications

Michael Soskind, Rose Soskind, Rutgers, The State Univ. of New Jersey (United States); Yakov G. Soskind, DHPC Technologies (United States)

We describe a novel coherent radiation enhancement technique and its application to laser beam shaping. The technique is based on the coherent transformation of the propagating radiation employing amplitude and/or phase structures, and produces localized radiation enhancements in the output plane. The described technique offers significant flexibility in generating a variety of output laser beam shapes. Employment of electronically controllable spatial light modulators in place of the phase or amplitude structures allows dynamic adjustment of the output laser beam patterns. We demonstrate the influence of various parameters on the resulting output radiation enhancement, including the impact of the shape of the propagating radiation as well as the shape and size of the phase structures. Our results indicate that by appropriately selecting the phase structure characteristics employed during the coherent radiation enhancement, a significant increase in the resulting peak intensity of the shaped beam is achieved.

9194-13, Session 3

Optimal diffraction-limited focusing through static aberrations

Gleb V. Vdovin, Flexible Optical B.V. (Netherlands) and National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Vsevolod Patlan, Oleg Soloviev, Flexible Optical B.V. (Netherlands)

Optimization of the point spread function by means of sensorless adaptive optics, based on direct imaging of the focal spot, suffers from errors due to enormous dynamic range of the focal intensity. Also, optimization algorithms based on the focal spot metrics only, are insensitive to other system parameters and can converge to “wrong” solutions. To improve the beam quality and the robustness of the global extremum, we have introduced dynamic feedback control of the camera sensitivity. To further increase the robustness of optimization, we introduced a regularization parameter in the form of some function of the system state, achieving its minimum together with the desired solution. Significant gain in achievable beam quality is shown in comparison with the implementation lacking those improvements. Proposed techniques are implemented in BeamTuner software for fine-tuning of laser and imaging systems with adaptive optics.

9194-14, Session 3

Fast hologram computation using GPU for optical tweezers

Huarong Gu, Qiaofeng Tan, Tsinghua Univ. (China)

Practical manipulation of particles by optical tweezers requires real-time computation of holograms. A large amount of calculation is required to trap and move hundreds of particles simultaneously. Common CPUs (Central Processing Units) are not able to fulfill this requirement. Whereas GPUs (Graphic Processing Units) have the unique advantages on parallel computing due to their large number of computing cores, thus GPUs are suitable for hologram computation. In this paper, fast hologram computation is realized on GPU for optical tweezers. The phase retrieval algorithms and the architecture of CUDA (Compute Unified Device Architecture) are studied. The phase retrieval algorithms are compared, optimized and implemented on CUDA. Windows programs based on CUDA are created to verify the advantages of GPU. The holograms are computed at a video frame rate, and uploaded on a phase-only spatial light modulator. Multiple dynamic optical traps are formed on the focal plane of an objective lens, which are used to trap and move cells.

9194-15, Session 4

Laser beam shaping: adoption into industrial laser applications *(Invited Paper)*

Todd E. Lizotte, Hitachi Via Mechanics (USA), Inc. (United States)

No Abstract Available

9194-16, Session 4

Characterization and application of bubbles during thermal blooming

Ujitha A. Abeywickrema, Univ. of Dayton (United States); Neil T. Banerjee, Centerville High School (United States)

When a highly absorbing thermal medium is heated with a focused high power laser beam, diffraction ring patterns can be observed due to self phase modulation (SPM). In our previous work, we introduced a simple interferometric technique using a probe beam to calculate the change of the refractive index of a thermal medium. It can be seen that when pump power increases, the usual SPM diffraction patterns change due to formation of a bubble inside the thermal lens created by the focused pump beam. This phenomenon, called thermal blooming, is the next step to SPM. In this work, a way of tracking the bubble using digital holography is introduced as a continuation of our earlier study on induced refractive index calculations. A 514 nm Argon-Ion laser is used as the pump and a 633 nm low power He-Ne laser is used as the probe. The thermal medium comprises a mixture of a red dye and isopropyl alcohol. To minimize the optical effects arising from convection, the focused pump is introduced vertically into the liquid sample. Inline holograms are recorded using the probe and numerically reconstructed using Fresnel propagation technique in order to determine the size of the bubbles. Bubble sizes are monitored as a function of the pump intensity. Maneuverability of the bubbles using the pump beam is investigated. Finally Ag nanoparticles are introduced into the thermal medium. The effect of possible nanoparticle agglomeration around the thermally generated bubbles is tested using a focused probe beam at a wavelength (viz., 405 nm) corresponding to the absorption peak of the nanoparticles.

9194-17, Session 4

Obsidianus lapis cutting, ablating, melting parameter calculation using a pulsed re-doped fiber laser

Alfredo I. Aguilar-Morales, Jose A. Alvarez-Chavez, Ctr. de Investigación e Innovación Tecnológica (Mexico); Jesus S. Velazquez, Ctr. de Investigación en Ciencia Aplicada y Tecnología Avanzada (Mexico); Sigifredo SM Marrujo, Ernesto EG Gonzalez, Ctr. de Investigación e Innovación Tecnológica (Mexico)

Obsidian is a volcanic rock that has been worked into tools for cutting or weaponry by Teotihuacan people for hundreds of years in central Mexico. Currently it is used in jewelry or for house decorative items such as elaborated sculptures. From the physico-chemical properties point of view, obsidian is considered a glass as its composition is 80% silicon dioxide. In México there are different kinds of obsidian according to its colour: rainbow, black, brown, red, silver, golden and snowflake. The traditional cutting process for working with obsidian includes a diamond blade, where the craftsman cut the stone manually obtaining a variety of shapes to continue with the grinding process. Laser processing of natural stone is a relatively new topic. We propose the use of an Yb^{3+}- doped fibre laser for cutting and ablating obsidian. We will focus in theoretical

aspects of absorption and material characterization, obtaining laser average power of up to 300W at 1um for melting-ablating obsidian small volumes and will theoretically calculate energy requirements of the fusion cutting from the proposed Q-switched fibre laser. Details on the full design and analysis on different peak power and pulse energy will be included in the presentation.

9194-18, Session 4

1 Tbps superchannel generated by optical flat comb source WDM-Nyquist and OFDM system simulative investigation

Hraghi Abir, Mourad Menif, SUP'COM (Tunisia)

Due to the enormous demand of Internet data traffic, future optical networks are expected to sustain services upgrades to data rates of 1 Tbps and beyond. Over all possible solutions, two promising solutions have attracted a great deal of attention, which are multicarrier techniques such as Wavelength Division Multiplexing-Nyquist (WDM-Nyquist) and Orthogonal Frequency Division Multiplexing (OFDM).

In this work, we implement an Optical Flat Comb Source generating a coherent super-channel operating at 1 Tbps using WDM-Nyquist and OFDM approaches with new flex-grid channel spacing. The new flex-grid defines WDM channel spacing having a multiple of 12.5 GHz. We compare through simulation the performance of two techniques for generating Dual Polarization-Quadrature Amplitude Modulation based on 16 (DP-16QAM), 64 (DP-64QAM) and 128 (DP-128QAM). We first study the performance of WDM-Nyquist and OFDM super-channels implementing DP-16QAM, DP-64QAM and DP-128QAM in back-to-back scenarios in terms of receiver sensitivity and Optical Signal-To-Noise Ratio (OSNR) requirement with 12.5 GHz flex-grid spacing. We find that DP-16QAM has the best receiver sensitivity and the lower OSNR penalty compared to the other modulation formats in WDM-Nyquist system. With DP-128QAM sensitivity as reference, we can observe a benefit of 10 dB for DP-16QAM with a BER equal to 3.8 10-3. In addition, we can observe a benefit of 12.4 dB in OSNR for DP-16QAM compared to DP-128QAM for a BER equal to 3.8 10-3. Also, we study the impact of the optical and electrical shaping filters. We compare the raised-co-sine shape optical filter case with the Gaussian optical one in a cascade of optical add-drop multiplexer (OADM). In each case, we evaluate the performance with using different electrical filters (rectangular, second order super-Gaussian, fourth order Chebyshev,…). Finally, we investigate the performance of WDM-Nyquist and OFDM terabit system with 12.5 GHz flex-grid spacing over long-haul dispersion compensated links using Standard Single Mode Fiber (SSMF). We find that DP-16QAM is the suitable modulation format in dispersion compensated WDM-Nyquist systems using SSMF fiber. Also, we prove that the use of Raman amplification improve the maximum reach of the super-channel by increasing the span distance between the amplifier module. Indeed, using the Raman amplification the maximum reach increase from 700 km to 1000 km in a WDM-Nyquist system based on DP-16QAM with 12.5 GHz flex-grid spacing.

9194-19, Session 5

Dynamic beam shaping with freeform optics *(Invited Paper)*

Thomas J. Suleski, Jason A. Shultz, Paul J. Smilie, The Univ. of North Carolina at Charlotte (United States)

Laser beamshaping, such as the classic example of changing a Gaussian input beam to a uniform 'flat-top', has found extensive uses in fields ranging from laser-based manufacturing to optical data storage, to medical applications, among others. The ability to change the output light distribution is desirable for many applications, but traditional approaches to achieve this goal can require incorporation of additional optics (e.g. zoom lenses) that can increase the size of the optical system, or fabrication and insertion of a new beamshaping element.

In this paper, we discuss the creation of dynamic beamshaping systems enabled by freeform optical surfaces. We focus on light transmission through multiple freeform surfaces in very close proximity, resulting in wavefront modification from the surface combination. Small, controlled relative motions between the surfaces enable dynamic changes in optical functionality. This approach enables both variable beamshaping as well as creation of compact optical systems. Examples for variable beamshaping systems with radial, square, and rectangular outputs are presented, as well as an optical system which accepts a variable input beam while maintaining a flat-top output spot of fixed dimension and location. General design approaches are discussed, and results from both geometrical and wave-based simulations using Zemax™ and LightTrans VirtualLab™ are presented. We consider fabrication approaches to realize the desired freeform surfaces and present experimental results demonstrating variable beamshaping.

9194-20, Session 5

Laser beam shaping with nanostructured lens

Zhengtong Liu, Eng Huat Khoo, A*STAR Institute of High Performance Computing (Singapore); Andrew C. Y. Ngo, A*STAR Institute of Materials Research and Engineering (Singapore); Liying Hong, Rui Fen Wu, DSO National Labs. (Singapore); Jing Hua Teng, A*STAR Institute of Materials Research and Engineering (Singapore)

Laser beam shaping is a widely used technique in many application areas, such as material processing like cutting and drilling, lithography, optical data storage, and medical procedures like corneal surgery. In most cases a laser beam shaping system consists of conventional lenses with curved surfaces. However these lenses are bulky and their fabrication precision are limited. In this work, we design and fabricate lens for laser beam shaping using nano-structures. The lenses are designed with traditional geometrical optical methods, using energy conservation and optical coordinate transformation algorithms. But instead of using curved surfaces to implement the lens designs, we choose to realize the designs with dielectric nano-structures. The lenses are then fabricated using electron beam lithography to achieve a high precision. The fabricated lenses have very low profiles and are capable of fine tuning laser beams, and they are experimentally tested. In the experimental setup a laser beam is directed into a multimode fiber and the irradiance of the output beam irradiance profile is measured. Then the lenses are placed in front of the multimode fiber and the outcome beam irradiance profile is measured again to test the effects of our laser beam shaping lenses.

9194-21, Session 5

Experimental characterization of variable output refractive beamshapers using freeform elements

Jason A. Shultz, Paul J. Smilie, Brian S. Dutterer, Matthew A. Davies, Thomas J. Suleski, The Univ. of North Carolina at Charlotte (United States)

We present experimental results from variable output refractive beamshapers based on freeform optical surfaces. Two freeform elements in close proximity comprise a beamshaper that maps a circular Gaussian input to a circular 'flat-top' output. Different lateral relative shifts between the elements result in a varying output diameter while maintaining the uniform irradiance distribution. We fabricated the beamshaping elements in PMMA using multi-axis milling on a Moore Nanotech 350FG diamond machining center and tested with a 632.8 nm Gaussian input. Initial optical testing confirmed both the predicted beamshaping and variability functionality, but with relatively poor output uniformity. Additional research shows the importance of the surface finish of the freeform surfaces in relationship to the output spot quality. The effects of surface finish on optical performance were investigated using LightTrans VirtualLab™ to perform physical optics simulations of the milled

freeform surfaces. These simulations provided an optimization path for determining machining parameters to improve the output uniformity of the beamshaping elements. A second variable beamshaper based on a super-Gaussian output was designed and fabricated using the newly determined machining parameters. Experimental test results from the second beamshaper showed outputs with significantly higher quality, but also suggest additional areas of study for further improvements in uniformity.

9194-22, Session 5

Modelling of a reflective waveplate for high-power lasers

Robert I. Heathcote, Rutherford Appleton Lab. (United Kingdom); Samuel Buck, James S. Green, Robert J. Clarke, Science and Technology Facilities Council (United Kingdom)

The polarisation state of a laser has a huge bearing on the physics of laser-plasma interactions and it is often desirable to change between linear and circular polarisation. For short pulse high power lasers, large beam apertures are necessary for transportation. However, in these extreme conditions transmissive birefringent polarisation optics become impractical due to their delicacy and their dispersion of the laser bandwidth. The dispersion can increase the pulse length, which along with large B-integral that arise from the transmission of the high power beams through optics, can be detrimental to the intensity of the laser. It is therefore necessary to consider reflective optics in order to change the polarisation. Modelling has been performed at the Central Laser Facility on the design of a large aperture broadband reflective polariser suitable for short pulse laser systems.

9194-47, Session 5

Laser beam transformations with anamorphic optics *(Invited Paper)*

Yakov G. Soskind, DHPC Technologies (United States)

Anamorphic optics plays an important role in several photonics applications.

In this paper we review several important applications of anamorphic optics in laser instrumentation, including:

- Beam shaping and combining
- Determining laser beam quality and propagation characteristics
- Transformations between various spatial modes

We show that anamorphic lens systems provide significant flexibility in producing a variety of output laser fields, and offer an important insight into formation of laser mode structures.

Several examples illustrate the formation of various structured laser fields employing anamorphic optics. The influence of the input laser field characteristics, including the mode structure, size, ellipticity and angular orientation onto the resulting transformed laser field will be discussed in detail.

We also show that by meting specific design requirements for the anamorphic optical system the propagation invariance of the transformed laser fields can be preserved.

9194-48, Session 5

The role of phase singularities in iterative beam shaping

Carlos López-Mariscal, U.S. Naval Research Lab. (United States)

A numerical assessment of the influence of phase vortices in a coherent landscape is presented. A correlation between the prevalence of phase singularities and the quality of coherent images formed iteratively is investigated and an upper bound to the quality is found experimentally that limits the performance of the iterative method. Several examples of varied complexity are examined and the results are interpreted in connection with the Shannon entropy.

9194-23, Session 6

Multi-functional diffractive optical elements *(Invited Paper)*

Anand Vijayakumar, Shanti Bhattacharya, Indian Institute of Technology Madras (India)

Diffractive optics has traditionally been used to transform a parallel beam of light into a pattern with a desired phase and intensity distribution. One of the advantages of using diffractive optics is the fact that multiple functions can be integrated into one element. Although, in theory several functions can be combined, the efficiency reduces with each added function. Also, depending on the nature of each function, feature sizes could get finer, especially at the edges of the element. Optical lithography with its 1 um limit becomes inadequate for fabrication and sophisticated tools such as e-beam lithography and focused ion beam milling are required. In this talk, I will present a number of composite elements. The main function of each element involves at least one circularly symmetric structure such as a Fresnel Axicon. In particular, we have designed diffractive optics assuming the light source to be close to the element, a feature useful when building compact systems. In this case, the diffractive element includes the desired function as well an aberration correction required due to the proximity of the source. Fabrication and optical results for each element will be presented in detail.

9194-24, Session 6

Building achromatic refractive beam shapers

Alexander V. Laskin, AdlOptica Optical Systems GmbH (Germany); David L. Shealy, The Univ. of Alabama at Birmingham (United States)

Achromatic beam shapers can provide beam shaping in a certain spectral band and are very important for various laser techniques, such as, applications based on ultra-short pulse lasers with pulse width <100 fs, confocal microscopy, multicolour holography, life sciences fluorescence techniques, where several lasers in spectrum 405-650 nm are used simultaneously, for example 405-650 nm. Conditions of energy re-distribution and zero wave aberration are strictly fulfilled in ordinary plano-aspheric lens pair beam shapers for a definite wavelength only. Hence, these beam shapers work efficiently in relatively narrow, few nm spectrum. To provide acceptable beam quality for refractive beam shaping over a wide spectrum, an achromatizing design condition should be added. Consequently, the typical beam shaper design contains more than two-lenses, to avoid any damaging and other undesirable effects the lenses of beam shaper should be air-spaced. We suggest a two-step method of designing the beam shaper: 1) achromatizing of each plano-aspheric lens using a buried achromatizing surface (“chromatic radius”), then each beam shaper component presents a cemented doublet lens, 2) “splitting” the cemented lenses and realizing air-spaced lens design using optical systems design software. This method allows for using a principle for achromatic design during the first step of the design, and then, refining the design by using optimization software. We shall present examples of this design procedure for an achromatic Keplerian beam shaper and for the design of an achromatic Galilean type of beam shaper. Experimental results of operation of refractive beam shapers will be presented as well.

9194-25, Session 6

Beam transformation: the universal tool for beam-quality manipulation

Thomas Mitra, Udo Fornahl, Mikhail M. Ivanenko, Manfred Jarczynski, Anna Lisa Kleinschmidt, Jens Meinschien, Yuri V. Miklyaev, Alexei S. Mikhailov, LIMO Lissotschenko Mikrooptik GmbH (Germany)

Micro optics are well-known for beam shaping for almost all kinds of lasers. Collimation or etendue matching is one major field of application, homogenizing and field or line generation is another one.

This paper focusses on the anamorphotic manipulation of beam parameters as divergence, beam size or beam quality by means of micro optic lens arrays. Such approaches are relevant on one hand where beam symmetrization is required, typically for fiber coupling of diode laser bars, and on the other hand where inherently an asymmetric beam quality is needed, e.g. for the generation of long and narrow line foci. Basically, beam transformation reduces the etendue in one axis of a beam while increasing the etendue of the perpendicular axis.

Basic principles as well as specific designs for instance for diode laser fiber coupling and small homogeneous lines of multimode DPSSL are presented. Examples of enhanced designs for beam symmetrization cover very compact and low loss multi stage arrangements for laser diode bars. For green and UV multimode DPSSL, the concepts allow beam shaping of long and very narrow lines. Recent set ups allow now the generation of line beams of 25 µm widths and lengths of 200 mm and more. Measurement results of such high brightness and homogenous line arrangements are shown.

Finally, beam transformation by means of micro optics lens arrays is a very efficient and comfortable approach to match the beam properties of the light source to the requirements of the application.

9194-26, Session 6

Designing refractive beam shapers via aberration theory

Alexander V. Laskin, AdlOptica Optical Systems GmbH (Germany); David L. Shealy, The Univ. of Alabama at Birmingham (United States)

In this paper, we use aberration theory to design a refractive laser beam shaper in the configuration of two-aspheric lenses, whose analytical equations are known, but rather complicated. Specifically, we use results from third order aberration theory to obtain the parameters of the refracting laser beam shaper from the transverse aberration, which are then used as a starting point for further optimization by using optical design software. This approach was developed during the beginning of the twentieth century, works well for systems with a low numerical aperture, and allows one to define the following parameters of an optical system: radii of curvature, indices of refraction, thicknesses or air gaps, and conic constants of second order aspheric surfaces. We shall consider surfaces of the second-order spherical and conic sections and shall consider the example of designing of a two-lens beam shaper of the Keplerian 1-to-1 telescopic design providing a theoretical flat phase front and a flat-top irradiance profile of the output beam, where the ray mapping function from the input aperture to the output aperture is known from the literature. Explicit expression for third order longitudinal aberration and the Seidel coefficients are expressed in terms beam waist and input beam geometrical parameter, indices, lens radii and conic constants.

9194-27, Session 6

Monolithical aspherical beam-expanding systems

Ulrike Fuchs, asphericon GmbH (Germany); Sabrina Matthias, asphericon Inc (United States)

Passive optical elements are essential in basically all laboratory applications and in complex laser systems, such as those for material processing. To match the beam diameters is a common task and mainly Galileo type telescopes are used to expand the beam.

However various limitations where found while using these systems in practice like adjustment complications, very small diameter for the incoming beam (1/e?), fixed and non-modifiable magnifications. Furthermore the beam expanders have only a diffraction-limitation optical design and can not guarantee for a diffraction-limited wavefront while operating.

In this paper we will discuss limitations of currently used beam expanding systems and present the benefits of a new monolithical solution which is based on the usage of only one aspherical component. We will show theoretically a significant improvement of the beam quality by using aspherical lenses. Due to the aspherical behavior a diffraction limited design is always given. We will present the possibility of a diffraction limited beam quality even while combining up to five monolithical beam expanding systems and the latest measurement data of the culminated wavefront error will be shown. Moreover an insight of how beam expanding systems based on aspheres will help to use larger incoming beams and to reduce the overall length of systems will be described. Finally, we will present an add-on element, which allows for wavelength tuning and adaption of divergence of the incoming beam.

9194-39, Session PMon

Techniques to measure complex-plane fields

Angela Dudley, CSIR National Laser Ctr. (South Africa); Nombuso Majola, Naven Chetty, Univ. of KwaZulu-Natal (South Africa); Andrew Forbes, CSIR National Laser Ctr. (South Africa)

In this work we construct coherent superpositions of Gaussian and vortex modes which can be described to occupy the complex plane. We demonstrate how these fields can be experimentally constructed in a digital, controllable manner with a spatial light modulator. Once these fields have been generated we illustrate, with three separate techniques, how the constituent components of these fields can be extracted, namely by measuring the intensity of the field at two adjacent points; performing a modal decomposition and a new digital Stokes measurement.

9194-40, Session PMon

Determination of the transverse size of an extended source using partially coherent vortices

Adad Yepiz Escalante, Benjamin Perez-Garcia, Raul I. Hernandez-Aranda, Tecnológico de Monterrey (Mexico); Grover A. Swartzlander Jr., Rochester Institute of Technology (United States)

A means to measure the transverse extension a partially coherent source through correlation measurements is presented. Our experiment employs a wavefront folding interferometer to study the cross correlation function of a partially coherent vortex, generated from an extended source. The cross correlation function of the vortex exhibits a ring dislocation whose diameter is closely related to the transverse extent of the partially coherent source. Excellent agreement exists between our theoretical and experimental results.

9194-41, Session PMon

Focal shift of dual auto-focusing Airy beams

Jorge A. Garza, Photonics and Mathematical Optics Group (Mexico); Raul I Hernandez-Aranda, Tecnológico de Monterrey (Mexico)

The intensity distributions of self-focusing of dual Airy beams are studied analytically by means of their statistical moments. Closed form expressions are derived that allow the determination of the focal shift through two different criteria; the first one is based on the second moment of the intensity whereas the second takes advantage of the beams symmetry to employ encircled-power calculations for defining the focus. Our results confirm the existence of a focal shift as expected, and show an effective quadratic dependence on the truncation parameter of the Airy beams.

9194-42, Session PMon

Non-uniformly correlated partially coherent beams and pulses

Toni Saastamoinen, Hanna Lajunen, Univ. of Eastern Finland (Finland)

The coherence properties of electromagnetic fields affect their propagation by determining the strength of the interference processes occurring between different points of the field. In most studies on partially coherent beams the correlation distribution is assumed to follow the Schell-model where the complex degree of coherence between two points depends only on their spatial distance. However, it has recently been shown that spatially varying, non-uniform coherence distributions can affect the propagation of beams in various ways. Analogous results have also been presented for the temporal evolution of plane-wave pulses propagating in dispersive media.

In this work we theoretically study the possibilities for controlling the propagation of beams and pulses by modifying their coherence distributions. The theoretical models existing for stationary beams and plane-wave pulses are generalized to include also pulsed beams. The propagation characteristics of the obtained non-uniformly correlated partially coherent fields are studied by numerical simulations for example cases. It is shown that extraordinary propagation-induced changes, such as self-focusing and laterally shifted intensity maxima, can be obtained with suitable initial coherence distributions.

Partially coherent fields with the considered characteristics may not be directly obtained from the currently available basic light sources. However, it is expected that they could be produced, e.g., from laser beams by different coherence-modulating schemes using, for instance, spatial light modulators. In conclusion, our results imply that tailoring of the coherence properties could offer a novel alternative way to shape and control optical beams and pulses.

9194-43, Session PMon

Laguerre Gaussian beam multiplexing through turbulence

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Recently a technique, known as mode division multiplexing (MDM), got a lot of attention from researchers around the world. MDM offers the possibility to scale the capacity of a single channel transmission system by several orders of magnitude in order to satisfy the upcoming capacity demand. In this context we are interested in multiplexing Laguerre Gaussian (LG) modes in free space.

In this paper, we present experimental results of multiplexing and de-multiplexing of LG modes using spatial light modulators. Importantly, the multiplexing digital holograms are encoded by complex amplitude modulation. Using a complete modal decomposition technique, we show that we are able to detect the phase and the amplitude of initially excited modes with high fidelity. We also demonstrate the simulation of atmospheric turbulence in the laboratory using a turbulence plate. We discuss the impact of different turbulence strengths on the purity of the multiplexed modes after de-multiplexing. We consider this work to be helpful in the case of high bit rate optical communication.

9194-44, Session PMon

Digital holograms for laser mode multiplexing

Thandeka I. Mhlanga, CSIR National Laser Ctr. (South Africa); Abderrahmen Trichilli, Univ. of Carthage (Tunisia) and Engineering School of Communication (Tunisia); Angela Dudley, CSIR National Laser Ctr (South Africa); Darryl Naidoo, CSIR National Laser Ctr (South Africa) and University of Kwazulu-Natal (South Africa); Mourad Zghal, Univ. of Carthage (Tunisia); Andrew Forbes, CSIR National Laser Ctr (South Africa) and University of Kwazulu-Natal (South Africa)

High-capacity data transmission has been implemented using single channel optical systems. This technique is limited and soon it will be unable to fulfill the growing needs for higher bit rate data transmission. Hence multi-mode transmission has been recently given attention as a potential solution to the current problems. We demonstrate a method of multiplexing laser modes classically using spatial light modulators (SLMs). SLMs can be addressed with appropriate digital holograms in order to create any desired modes, from single to multi-modes. In our proposed technique, we use Laguerre Gaussian (LG) modes, which forms a complete basis set; hence multi-mode digital holograms can be created by taking a linear combination of the LG modes.

These LG modes are characterised by two degrees of freedom, the azimuthal index ? and radial index p, which in principle allows higher-dimensional states, and can be useful for increasing information transmission capacity. There are some experimental challenges associated with this method; these include the sensitivity of the setup to wavefront aberrations, which introduces cross-talk between the multi-modes. It is also important that the injected modes carry the same power; so that they can be weighted equally as they propagate to be decomposed. The size of the multi-modes is highly dependent on the resolution of the SLM which is limited to 1920x1080 pixels.

9194-45, Session PMon

Beam propagation in a uniaxial crystal under small angle to the optical axis and arrays of bottle beams.

Maksym Ivanov, Natalia V. Shostka, Taurida National V.I. Vernadsky Univ. (Ukraine)

We numerically built model of laser beam shaping of asymmetrical and symmetrical arrays of bottle beams generated by uniaxial crystal. We considered initial arrays of Gaussian beams as well as initial singular beam array (i.e. array of optical vortices) shaped before uniaxial crystal by computer-synthesized hologram. Then we inspect types of bottle beam arrays generated by the crystal, and processes of interference of beams within the arrays. Also polarization distribution of symmetrical and asymmetrical structures was shown. We examined experimentally

generation of arrays of bottle beams by uniaxial crystal of LiNbO3 as well as polarization and intensity distribution. Numerical and experimental results was compared for array of N beams, N = 1, 2, 3, 5, 6, 8. Also we compared numerical and experimental dependence of rotation of array on the inclination angle of asymmetric and symmetric bottle beam arrays which consist of N particular bottle beams.

9194-46, Session PMon

Optical vortex in microscopy imaging

Mateusz M Szatkowski, Jan Masajada, Agnieszka Popiolek-Masajada, Wroclaw Univ. of Technology (Poland)

The optical vortex is a stable phase dislocation. We use optical vortex in microscopy imaging. The optical vortex scanning microscope (OVSM) uses a focused laser beam with an optical vortex to scan the sample. We present the new optical setup of the OVSM which is based on the carrier frequency interferometry. The optical vortex is introduced by spiral phase plate. The spiral phase plate is mounted on the motorized table. By shifting this plate the optical vortex moves inside the focused beam. The vortex point inside focused spot (after the microscopic objective) moves at much smaller range comparing to the spiral phase plate shift. Vortex point travels along the straight line, when the plate moves along the straight line. What is more the inclination of the vortex trajectory depends on the observation plane position. The vortex point moves perpendicularly to the plate shift in place where the focused spot has the smallest diameter. We call this plane “critical plane”, there the vortex point is very sensitive for the sample topography. This opens a new possibilities for sample scanning. The new experimental results will be presented. We tested new design by measuring objects with different topographies: optical wedge, groove and diffraction grating.

Reference:

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9194-28, Session 7

Propagation of optical vortices with fractional topological charges in free space

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The behavior of optical vortices with fractional topological charges in a near and far-field are described, including performing by numerical modeling that are confirmed by experimental results.

To generate beams with fractional topological charges, we introduced fractional (non-integer) topological charge variations of the phase within a Gaussian beam by using a liquid-crystal of silicon spatial light modulator (LCoS SLM).

By creating the phase mask with different topological charges, especially with the fractional topological charges, it was observed that the laser beam having a fractional topological charge in near-field tends to have a topological charge of integer value in the far-field, with an integer value that is closer to the fractional number. The result was observed for beams with topological charges of 2.2, 2.5, 2.7. The beams having topological charges of 2.5 and 2.7 shown the presence of three single vortices in the far-field, whereas the beam with topological charge 2.2 shown the presence of only two single vortices (indicative of topological charge 2) because the excess amount of topological charge above 2 for this beam is less than ?.

The behavior of a single beam with two different topological charge embedded by LCSLM is also modeled and experimentally studied. An unusual behavior is observed on the example of the laser beam with embedded optical vortices with topological charge 2.2 and 2.7: a beam with five single optical vortices has been generated.

We studied evolution of the laser beams with one or more fractional topological charges embedded by LCoS SLM.

9194-29, Session 7

Compact optically-actuated high-power laser beam delivery system for industrial metal processing applications

Ian A Baker, Nick Hay, HyeonSeok So, Young Key Kwon, Powerlase Photonics Ltd. (United Kingdom)

Development of novel metal products and processing techniques are generating new industrial challenges and applications, this is turn is generating a need for the development of full laser delivery systems incorporating many separate engineering disciplines.

This project was to develop a complete high power laser beam delivery and tracking system to meet challenging space and accuracy requirements for a processing application in the metal processing industry. Current systems available on the market could not satisfy the space constraints nor meet the criteria for the production, so a prototype solution was developed at Powerlase Photonics in partnership with the customer.

A system design approach was taken, designing custom components for the application, namely the laser, beam shaper, actuator and control electronics and then integrating with commercially available components to complete a new system capable of meeting the required needs.

The complete system consists of a high power infrared pulsed laser, a vision system, customized electronics and customized optics, incorporating designs for beam homogenising and beam shaping.

The laser beam was homogenized using a square form fibre and imaged onto the substrate via a beam shaping optical relay, this provided an idealized rectangular beam profile with excellent homogeneity. A Risely actuator was placed within the optical path, such that the angular displacement of the prisms directly created a spatial displacement of the beam upon the substrate. Optical modeling techniques were used to ensure the beam quality, homogeneity, spot size, was maintained across the entire range of motion. The system was also designed such that the beam would be safely terminated even if the actuation system completely misaligned or failed, an important consideration given then average power of the laser beam.

Electronics and firmware signal processing development was also undertaken, in order to maintain process stability encountered in the realities of the industrial environment.

The following results were obtained across the entire actuation range +/-6 mm, delivered beam variance <5%, homogeneity <20%, change in delivered power <5% (even under failure condition). Target tracking accuracies were typically 50-100 um in production but beam steering with this method is capable of resolutions <2 um.

The prototype system is now running in serial production.

9194-30, Session 7

Modeling the effect of spatial filter plasma emission on high-intensity laser beam propagation

Will Riedel, Eyal Feigenbaum, Charles D. Boley, Richard A. Sacks, Kathleen McCandless, Clay C. Widmayer, Steven T. Yang, Joseph T. Salmon, Kenneth S. Jancaitis, Kai N. LaFortune, Shamasundar N. Dixit, Charles D. Orth, Ronald K. House, Jean-Michel G. DiNicola, Michael J. Shaw, Brian J. MacGowan, Lawrence Livermore National Lab. (United States)

The National Ignition Facility (NIF) laser generates infrared pulses with 4TW peak powers per beam-line. When these powerful beams are focused through the spatial filters pinholes the beam edges illumination on the pinhole walls generates plasma that expands into the beam-path. The NIF employs a conical pinhole design in order to minimize the disruption of the beam by this effect. Here we examine the effect on the pulse tail by the refractive index modifications of the plasma, as created by the pulse front.

We have made usage of a model for the electron distribution in space and time, based on measurements in a previous laboratory experiment. We used a Drude model for the plasma refractive index and modified a Talanov-type Fourier beam propagation code to allow propagation through the focal plane of the spatial filter. In this model, each time slice propagates through a spatially-varying index that is generated by the influence of previous slices.

We examined typical NIF beams at the entrance of the Transport Spatial Filter, where the beam power is maximal. We studied the sensitivity of pinhole phenomena to beam edges spatial profile. Typical electron densities, refractive index distributions, and the resulting modifications to the beam shape at the image plane will be presented. At typical operating powers, this effect gives rise to hot rim modifications in the beam shape, resulting from asymmetry of the injected beam shape. The maximum predicted intensity increase is less than 1%, which is acceptable for NIF operation.

(This_work_was_performed_under_the_auspices_of_the_U.S._Department_of_Energy_by_Lawrence_Livermore_National_Laboratory_under_Contract_DE-AC52-07NA27344._LLNL-ABS-649013)

9194-31, Session 7

Direct synthesis of the laser beam with pre-determined intensity distribution by means of intracavity adaptive optics

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We consider a problem of direct synthesis of the laser beam with pre-determined intensity distribution, by means of intra-cavity adaptive optics. The mathematical formulation of the problem is reduced to the study of the solutions of the resonator equation, expressed in tems of the field amplitudes and phases inside the resonator, and the parameters of resonators that

includes the deformable mirror. It is shown that, with some assumptions, the shape of the deformable mirror can be expressed as a function of the output intensity distribution. The results of direct numerical simulations agree with the obtained analytical estimates. Experimental verification is in progress.

9194-32, Session 7

Three-dimensional self-similar fractal light in canonical resonators

Steven W. Miller, Univ. of Glasgow (United Kingdom); John Nelson, Univ. Paris 7-Denis Diderot (France); Johannes Courtial, Univ. of Glasgow (United Kingdom)

Unstable canonical resonators can possess eigenmodes with a fractal intensity structure [Karman et al., Nature 402, 138(1999)]. In one particular transverse plane, the intensity is not merely statistically fractal, but self-similar [Courtial and Padgett, PRL 85, 5320 (2000)]. This can be explained using a combination of diffraction and imaging with magnification greater than one: each round trip through the resonator adds approximately the same diffraction pattern to the resonator, which gets then magnified through imaging, resulting after many round trips in the diffraction pattern being present on a cascade of length scales, a hallmark of fractals.

Here we show that the same mechanism also shapes the intensity cross-section in the longitudinal direction. Combined with the mechanism for shaping the transverse intensity distribution, this results in three-dimensional, self-similar, fractal intensity structure in the lowest-loss eigenmode. Because the transverse and longitudinal magnifications are different, the scaling properties in the transverse and longitudinal directions are different. We demonstrate this structure using computer simulations.

9194-33, Session 7

Towards high-brightness lasers by intra-cavity mode control

Andrew Forbes, CSIR National Laser Ctr. (South Africa)

No Abstract Available

9194-34, Session 8

High-power CW CO2 laser-beam formation by means of adaptive optics

Alexis V. Kudryashov, Alexander B. Alexandrov, Vadim Samarkin, Julia Sheldakova, Alexey Rukosuev, Moscow State Univ. of Mechanical Engineering (Russian Federation) and Active Optics Night N Ltd. (Russian Federation)

In this presentation we consider the design and realization of wide aperture adaptive system to correct for high power CW CO_2 laser radiation. The results of such a correction using Hartmann wavefront sensor will be demonstrated.

9194-35, Session 8

Symmetrical output from corner-pumped TEM00 Nd:YAG laser operating in two stable regions

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As a new pumping method of LD pumped solid-state lasers, corner-pumped configuration is different from traditional ones such as end-pumped, edge-pumped and side-pumped configurations. It can be used in TEM00 lasers which have good beam quality. However, the waist sizes and divergence angles of the output beam of corner- pumped TEM00 laser are not equal in the width and the thickness directions of the corner- pumped composite slab. The asymmetrical output restricts the application of corner-pumped configuration.

To improve the symmetry of the output from the corner-pumped solid-state laser, we adopted a plane- parallel resonator design and placed the mirror in the long arm as the output coupler. Best pump and laser mode matching could be obtained by adjusting the length of the long arm. The laser spot on the output mirror with equal size could be obtained by adjusting the length of the short arm. Once the spot on the flat output mirror, which is the waist plane of both oscillating beam and output beam, is optimized with equal sizes in both directions, the waist sizes

and divergence angles of the output beam are equal in both directions. The experimental results showed the laser output had good symmetry at certain pump power and the symmetry still remained stable at a pump power range. Both theoretical analysis and experimental results indicated that the resonator design could be adopted to obtain the symmetric laser output with asymmetric thermal dioptric power, which is suitable for side-pumped, edge-pumped and corner-pumped configurations.

9194-36, Session 8

Hysteresis loop and pattern from the dual-wavelength competition in an Nd:YVO4 laser with an intracavity periodically-poled lithium niobate Bragg modulator

Kun-Guei Hong, National Cheng Kung Univ. (Taiwan); Shou-Tai Lin, Feng Chia Univ. (Taiwan); Ming-Dar Wei, National Cheng Kung Univ. (Taiwan)

This study demonstrates hysteresis loop and pattern formation in a Nd:YVO4 laser at 1064nm (4F3/2-> 4I11/2) and 1342nm (4F3/2-> 4I11/2) with an intracavity periodically poled lithium niobate (PPLN) Bragg modulator by using a T-type cavity configuration. Because the stimulated emission cross section of 1342 nm light is less than that of 1064 nm light, a T-type cavity configuration was proposed to achieve the tunable ratio of beam spot size between the wavelengths of 1064 and 1342 nm to enhance the extracting efficiency of 1342 nm. Based on the dual wavelengths sharing the upper energy level to lase, a PPLN was inserted in the arm of 1064 nm cavity to finely tune the loss of 1064 nm beam to explore the dynamics of dual-wavelength competition. A hysteresis loop occurred when the extracting efficiencies of dual wavelength were near equivalent. When the pump power was 7.7 W, the hysteresis loop was observed in the region of the transmission, T, of PPLN between T=54.2% to T=70.2%. The slope efficiencies were 14.1 and 2.1% and the thresholds were 4.2 and 4.0 W for the wavelengths of 1064 and 1342 nm, respectively. The rising transmission threshold of the loop increased as the pump power increased. Moreover, the hysteresis loop accompanied with the variation of the pattern formation. A high-order transvers mode was easily observed at 1342 nm light, but a simple spot existed for 1064 nm light. Apparently, the role of gain competition is worthy to deeply explore.

9194-37, Session 8

Coherent combining of four slab laser amplifiers with high beam quality

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Coherent beam combination (CBC) is an effective way to improve the output power and beam quality of laser system. In this paper, we report a coherent combining of four slab laser amplifiers with high beam quality. The long strip laser beam is reshaped into a square beam using adjustable beam expander which removes the enormous astigmatism aberration. A filling ratio of 90% is achieved by two-dimensional splicing. Compact optical system with high sampling frequency is designed to detect the pointing direction of lasers. Fast steering mirror (FSM) driven by piezoelectric ceramics is applied in laser stabilizing. Thanks to the closed loop pointing control, the root mean square error of the optical axis is significantly reduced to be less than 2 microradians. The piston phases of the lasers are locked by an active phase control system based on Field Programmable Gate Array(FPGA) using stochastic parallel gradient descent (SPGD) algorithm. When the total output power of four lasers is 400W, the in-phase peak intensity of the far field spot is increased by a factor of 3.8, reaching 95% of the ideal case. The beam quality of the combined beam is improved by CBC from 1.52x diffraction limit (DL) to 1.26x DL. When the output power is increased to 805W, the phase locking and pointing control still work stably. The results suggest that CBC of solid-state lasers with higher energy could be achieved by using the techniques presented here.

9194-38, Session 8

Generation and transformation of azimuthally and radially polarization in a typically three-element Nd:GdVO4 laser

Ken-Chia Chang, Ming-Dar Wei, National Cheng Kung Univ. (Taiwan)

In this work, azimuthally and radially polarized beams were achieved in the continue-wave Nd:GdVO4 lasers with a typically three-element cavity configuration. Because the birefringence of the laser crystal induce the optical path difference between the extraordinary ray and the ordinary ray, a laser cavity operating around the edge of a stable region will ensure that one ray is stable while the other ray is unstable. Under these conditions, the proposed cavity configuration would be suitable for generating an azimuthally or radially polarized beam. The preferred specific-polarization cavities were analyzed base on the ABCD law and were verified in experiments. Because the laser is directly obtained from a general cavity without adding intracavity element, azimuthally and radially polarized beam are the intrinsic lasing modes of the laser system with a birefringent gain medium. Moreover, the transform from radially polarization to azimuthal polarization by slightly tuning cavity length was observed when the cavity configuration operated around the preferred azimuthally polarized cavity configuration. This transition could be resulted from the efficiency of extracting energy for the extraordinary ray is greater than that for the ordinary ray before the extraordinary ray to be unstable. The degree of polarizations for azimuthally and radially polarized beams can be measured to be 92.4%±1.8% and 93.7%±3.7%, respectively; and the slope efficiencies are approximately 16.4% for both polarized operations.

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Conference 9195: Optical System Alignment, Tolerancing, and Verification VIII

Sunday - Monday 17–18 August 2014

Part of Proceedings of SPIE Vol. 9195 Optical System Alignment, Tolerancing, and Verification VIII

9195-1, Session 1

Modeling tip-tilt types of errors in optical tolerance analysis

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Many optical designs have lenses with round outer shapes that are consequently mounted in cylindrical barrels. Such geometry leads to errors on mounting parameters such as tip and tilt that are best modeled with a cylindrical coordinate system. Without clocking registration, this leads to the magnitude of the element tilt being represented as a tilt angle about a random clocking azimuth. Similarly, an element with wedge has a magnitude that is effectively a surface tilt along with a random clocking azimuth. It is important for optical engineers to fully understand this cylindrical basis geometry to most effectively perform tolerance assignment and analysis. Confusion can result from the fact that the majority of commercial optical design codes typically currently default to tolerance entries for these types of errors in Cartesian coordinates. This pedagogical paper covers the geometry and associated statistics associated with cylindrical geometry asymmetric errors for practicing optical engineers and designers.

9195-2, Session 1

Photonic Doppler velocimetry probe designed with stereo imaging

Robert M. Malone, Brian M. Cata, Edward P. Daykin, David L. Esquibel, Brent C. Frogget, National Security Technologies, LLC (United States); David B. Holtkamp, Los Alamos National Lab. (United States); Morris I. Kaufman, Kevin D. McGillivray, National Security Technologies, LLC (United States); Martin J Palagi, National Security Technologies LLC (United States); Peter D. Pazuchanics, Los Alamos National Lab. (United States); Vincent T. Romero, National Security Technologies, LLC (United States); Danny S. Sorenson, Los Alamos National Lab. (United States)

The velocity distribution of an imploding curved surface is measured with a miniature fiber-optic probe. The probe uses fiber matrix arrays that are focused onto different regions of this curved surface. A pyramid prism deflects the interrogation onto specific regions of this curved surface. The fiber arrays record velocity along several hundred lines of sight with sub-nanosecond resolution. Reflected light from each spot on the moving surface is Doppler shifted with a small portion of this light propagating backwards through the launching fiber. The reflected light is mixed with a reference laser in a technique called Photonic Doppler velocimetry, providing continuous time records.

Within the probe, seven sets of miniature optical relay lenses are grouped into a close-packed array, allowing the interrogation of seven regions of interest. A six-faceted pyramid prism with a conical hole drilled into its center is used to direct the light beams onto different regions. To minimize back reflections, the fiber matrix arrays are index matched onto the first relay lens made of fused silica. The optical lens design minimizes the laser beam diameters and also provides excellent imaging capabilities. Therefore, two of the fiber matrix arrays are replaced by coherent bundles for stereo imaging recorded by a high-speed framing camera. This requires additional cutouts of the pyramid prism to allow imaging overlap. Six additional 1.5 mm diameter incoherent bundles are attached to the edges of the pyramid prism and are used for illumination. Precision metrology on the direction cosines of the trajectories is measured to satisfy environmental requirements for vibration and temperature.

9195-3, Session 1

Optical design and tolerancing of an ophthalmological system

Ingo Sieber, Thomas Martin, Karlsruher Institut für Technologie (Germany); Allen Yi, Likai Li, The Ohio State Univ. (United States); Olaf Ruebenach, INGENERIC GmbH (Germany)

The loss of accommodation ability is an age-related process. Due to stiffening of the human crystalline lens, this ability generally is no longer provided sufficiently after the age of 50 years. A new approach to restoring accommodation ability is by means of a smart mechatronical implant i.e., by the Artificial Accommodation System. The optical subsystem of the implant consists of an aspherical optics integrated in the system's glass housing and fabricated by means of a precision molding process and a tunable optics for adapting the refraction power demanded. The tunable optics consists of freeform surfaces based on the functional principle invented by Alvarez and Humphrey. Fabrication is carried out by means of injection molding of polymethylmethacrylate.

To ensure manufacturability of the optics, the individual design rules of the different fabrication processes are considered. The processes involved allow for integration of adjustment and alignment structures into the optical components to reduce mispositioning.

Deviation of the surface shape due to fabrication tolerances and the alignment of the optical structures are critical for the system's functioning, especially concerning aspherical and freeform surfaces. Estimation of the fabrication inaccuracies of the surfaces turned out to be unfeasible. To be able to tolerance the optical subsystem, metrology data of the fabricated surfaces were integrated into the optical model.

The focus of this article is on designs for manufacturability of aspherical and freeform optics with integrated alignment structures and on tolerancing of the optical subsystem on the basis of the measured surface data of manufactured optical components.

9195-4, Session 1

Study on decentration-induced optical aberrations in an optical system using Shack Hartmann wavefront sensor

Venkataramana Kalikivayi, Indian Institute of Technology Madras (India) and Elite School of Optometry (India) and SASTRA Univ. (India); Krishna Kumar R., Elite School of Optometry (India); Kannan K., SASTRA Univ. (India); A. R. Ganesan, Indian Institute of Technology Madras (India)

Alignment of optical components is one of the important requirements in any optical system. Decentration of a component, like a lens, in the path of the beam, would introduce aberrations of various types. This would affect the measurement accuracy in the optical system such as an interferometer. In this work, we have analyzed the influence of decentration of an optical component on the wavefront in an optical system. The various aberrations caused due to the shifting of the axis of a lens in the path of an optical wavefront have been measured using a Shack Hartmann Wavefront Sensor and their influence studied. One of the lenses in the optical system is moved or decentered in transverse direction by 500 microns in steps of 50 microns. Decentration was done for all four quadrants. For each step, wavefront data is been taken and data was analyzed. Defocus, horizontal coma, vertical coma and spherical aberration were analyzed, apart from peak-to-valley and RMS values. Results showed that the error introduced is minimal up to 300 microns decentration, above which the aberrations were quite large. The experimental results and analyses are presented.

9195-5, Session 2

Tolerancing sub-aperture regions of optical surfaces using circular and elliptical Zernike polynomials

Chih-Yu Huang, College of Optical Sciences, The Univ. of Arizona (United States); Richard N. Youngworth, Riyo-LLC (United States); Rongguang Liang, College of Optical Sciences, The Univ. of Arizona (United States)

Zernike polynomials are orthogonal within a normalized circle. However, when optical surfaces are away from the stop, the beam size becomes smaller than the surfaces, and the Zernike polynomials are not orthogonal inside the illuminated region. In this paper, we investigate a method of using Zernike polynomials to fit sub-aperture regions illuminated by the optical beam in order to retain orthogonality. The method works for both on-axis and off-axis conditions. In some special cases where the optical beam is not circular, we develop a user defined surface that utilizes elliptical Zernike polynomials for the fitting. Finally, we provide an example and discuss the importance of the sub-aperture fitting to tolerance assignment and analysis of the surface.

9195-6, Session 2

Statistical distributions from lens manufacturing data *(Invited Paper)*

Morris I. Kaufman, National Security Technologies, LLC (United States); Brandon B. Light, Optimax Systems, Inc. (United States); Robert M. Malone, National Security Technologies, LLC (United States); Michael K. Gregory, Optimax Systems, Inc. (United States)

Optical designers assume a mathematically derived statistical distribution of the relevant design parameters for their Monte Carlo tolerancing simulation. Presented are measured distributions using lens manufacturing data to better inform the decision-making process.

9195-7, Session 2

Tolerances in panoramic lenses *(Invited Paper)*

Simon Thibault, Xavier Dallaire, Univ. Laval (Canada)

The development of panoramic imaging systems capable of transmitting high-resolution images in real time is critical in a variety of applications. Due to limited space-bandwidth product, the sampling of the image is limited. But by controlling the distortion (the magnification), we can define the sampling or the spatial frequency (lp/mrad) as function of the FOV like in Panomorph lenses. Like the artist using stretching in the spatial domain to display artistic perspective of images, the modern panoramic lenses use the selective spatial stretching to optimized panoramic image.

Almost every aspect concerning the optical design of those panoramic lenses brings new challenges to optical designers. Examples of these include ray tracing programs having problems finding the entrance pupil which is moving through the field of view, optimisation, production particularities due to the shape of the lenses, and ways of tolerancing these systems having strong distortion. This last topic will be discussed in the presentation.

9195-8, Session 2

Designing null screens type sub-structured Ronchi to test a fast plano-convex aspheric lens

Diana N. Castán Ricaño, Maximino M. Avendaño-Alejo, Univ. Nacional Autónoma de México (Mexico)

In order to evaluate either qualitative or quantitatively the shape of fast plano-convex aspheric lenses, a method to design null screens type sub-structured Ronchi is proposed. The null screens are formed with nonuniform curves which allows us to have both thin and thick monochrome strips between contiguous curves. The screens are printed on a light transmission modulator and placed in front of the lens under test, they are illuminated with a collimated monochromatic beam propagating along the optical axis, in such a way that through the process of refraction will form a uniform straight fringes pattern which are recorded at a predefined plane of detection, finally processing its image recorded we could be able to get a quantitative evaluation of the lens under test. The designs of these null screens are based on the equations of the caustic surface produced by refraction. The null screens can be printed in gray levels on a light transmission modulator depending on the applied voltage on it. A preliminary test for a fast plano-convex aspheric lens with f/#=0.8 is presented in this work. This method also could be applied to alignment of optical systems.

9195-9, Session 3

Analysis methodology for a piezoelectric-driven optical tracker for ground-based interferometry

James H. Clark III, U.S. Naval Research Lab. (United States); F. Ernesto Penado, Northern Arizona Univ. (United States)

We present our analysis methodology for a large aperture prototype optical tracker to reveal components that limit performance. The Navy Precision Optical Interferometer (NPOI) in Flagstaff, Arizona, makes use of six separate smaller optical telescope stations spaced along a 437 m Y-array and used simultaneously to simulate an equivalent single larger telescope. Piezoelectric driven optical trackers steer the output beam from each station to an optics laboratory anywhere from 100 m to 700 m away. A percentage of this starlight is split off, focused onto an electro-optical quad-cell detector and used in a closed loop feedback to update the pointing of the telescope and steering of the tracker. Position steering stabilizes atmospheric induced trajectory deviations and the final beam positions for interferometric fringe generation. The tracker mirror is aluminum coated Zerodur® first surface flat secured in aluminum alloy gimbals. Steering is controlled by 2-axis rotation of the mirror by extension of piezoelectric (PZT) actuators at the radius of the gimbal pivot for each axis. A 45 N spring-force, acting against extension, controls reverse steering during retraction of the actuator. The range of steering is 20 microradian with 0.2 microradian precision. The natural frequency of the tracker is 66 Hz and the position command update frequency is 22 Hz. This tracker stabilizes the recombination beams adequately for stellar fringe generation on a fair number of clear nights. We conclude the low fundamental frequency of the mount limits its performance. Stiffening the structure will allow an increase in command update frequency.

9195-10, Session 3

Imagery analysis and the need for standards *(Invited Paper)*

Barbara G. Grant, Lines and Lights Technology (United States)

While efforts within the optics community focus of necessity on the development of high-quality systems and data products, comparatively little attention is paid to their use. Our standards for verification and validation are high; but in some user domains, standards are either lax or do not exist at all. In forensic imagery analysis, for example, standards exist to judge image quality, but do not exist to judge the quality of an analysis. In litigation, a high quality analysis is by default the one performed by the victorious attorney's expert.

This presentation will argue for the need to extend quality standards into the discipline of imagery analysis by taking the necessary first step of

separating issues of fact from analysis results. "Is the sky blue or is it not?" falls into the former category; "Did the blue sky cause the robin to fall from his nest?" in the latter. It will use imagery obtained from the 1993 Waco FLIR imager to illustrate these differences.

Good practice in radiometric calibration encourages us to make the calibration as independent of the instrument as possible. This concept can be applied to improve the quality of imagery analysis, whose importance in civilian life will increase with the deployment of domestic UAVs.

9195-11, Session 3

Verification of a large off-axis mirror and tip-tilt controllers

Young-Soo Kim, Ju Heon Koh, Hwa Kyoung Jung, Ho June Jung, Jihun Kim, Korea Astronomy and Space Science Institute (Korea, Republic of); Myung K. Cho, National Optical Astronomy Observatory (United States); Ho-Soon Yang, Joohyung Lee, Korea Research Institute of Standards and Science (Korea, Republic of); Ho-Sang Kim, Kyoung-Don Lee, Institute for Advanced Engineering (Korea, Republic of); Hyo-Sung Ahn, Gwangju Institute of Science and Technology (Korea, Republic of); Won Hyun Park, Dae Wook Kim, Peng Su, The Univ. of Arizona (United States); Sug-Whan Kim, Yonsei Univ. (Korea, Republic of)

Fast Steering Mirror (FSM) is the first secondary mirror system of Giant Magellan Telescope (GMT), which will be used at the first light due in 2019. FSM contains tip-tilt mechanism to compensate wind and structural jitter effects. FSM is 3.2 m in diameter, and consists of seven segments. Each mirror segment is concave, 1.1 m in diameter, and light-weighted.

Korea Astronomy and Space Science Institute leads a consortium of R&D institutions in Korea and in USA for the development of the FSM prototype. The main purpose is to acquire the key technologies - fabrication of highly aspheric off-axis mirror and tip-tilt control. A full-size off-axis aspheric mirror segment of 1.1 m in diameter has been fabricated and its testing methods have been developed. About one hundred holes were drilled at the backside of the mirror to reduce the weight of the mirror. The front surface was ground and polished by using various sizes of abrasive tools. A laser tracker and two different types of CGHs were used for the testing. Additional tests, the Software configurable optical test system (SCOTS) and another type of CGH, are being conducted for confirmation.

Tip-tilt test-beds have been assembled to verify the characteristics of the tip-tilt mechanism. A dummy mirror, a mirror cell, three axial supports and a lateral support, and vacuum equipment are assembled and hung over test-bed frames. Tip-tilt range of 20 arc seconds and tip-tilt resolution of 0.02 arc seconds were achieved. Required image attenuations were accomplished by tip-tilt control up to 30 hz. Those were achieved at both directions of zenith and in 30 degrees inclined from zenith direction. We present the results of the successful developments.

9195-12, Session 3

Modeling and simulation of fast-axis collimator lens alignment for high-power diode laser bar

Jun Lei, Institute of Applied Electronics (China)

High-power diode lasers usually cannot be used directly for many applications such as disk or slab laser pump source because their large divergence angles in fast axis. Therefore, a collimation of fast axis for high power diode laser bar is necessary. In this paper, a model for fast-axis collimator lens alignment for high-power diode laser bar based on real setup is created. The simulation of the alignment is also completed by ray tracing technique. In order to obtain near diffraction limited beam, several factor, such as mounting error and smile effect, are considered. The simulation results shows that the diode laser bar with large smile effect reduce its beam quality significantly.

9195-13, Session 4

Issues with measuring tilt and decenter of small molded aspheric lenses

Robert E. Parks, Optical Perspectives Group, LLC (United States); William P. Kuhn, Opt-E (United States)

To get optimum performance from molded aspheric lenses the optical axes of the two aspheric surfaces must be well aligned in tilt and decenter. We discuss several approaches to interferometric testing to determine the tilt and decenter, and show how the prescriptions of the lens surfaces influence the choice of test depending on the desired precision of the test. Hidden in the aspheric coefficients are designs where the test can look perfectly straight forward and yet is difficult or impossible to perform with high-precision because of the surface shape. There are means to surmount these difficulties with optical tests but they are difficult to implement to the precision required in some applications. On the other hand, mechanical profiling can give the needed precision but such tests are lengthy compared to optical methods.

We discuss tradeoffs between the lens design and the methods of test in order to give the designer a feel for the bigger picture of optimization. There may be perfectly acceptable optical designs that yield surfaces that are also relatively easy to measure for tilt and decenter. We describe the surface shapes that make for easy testing as opposed to those that are difficult. Having designs whose surfaces are easy to test optically would make the overall manufacturing process more efficient by eliminating lengthy test cycles that are needed for control of the molding process.

9195-14, Session 4

Evaluating non-null optical systems with deflectometry

Weirui Zhao, Beijing Institute of Technology (China); Run Huang, Peng Su, James H. Burge, The Univ. of Arizona (United States)

There are optical systems where the purpose of the systems are not providing sharp images, but for widening the field of view of a particular imaging system, or illuminating targets, or being used for testing another system, or other purposes. In many cases, the performance of these systems cannot be well verified due to their non-null property. We propose to use SCOTS, a reflection/transmission deflectometry system, as a general tool to evaluate the performance of non-null optical systems.

SCOTS illuminates the system under test with a computer screen, and collect the images with a digital camera. SCOTS acts as a Hartmann test in reverse and measure the system wavefront slopes. By taking multiple SCOTS measurements with different camera positions, the field-dependent wavefront information of the system under test can be obtained. The multiple-field wavefront information can be used to reconstruct certain system configuration, alignment status, and system performance.

We verified our concept by measuring a two element null-lens system which was used for testing a large aspheric mirror. We also investigated the case of using SCOTS for verifying the alignment of the Hobby-Eberly Telescope (HET) wide field corrector where four highly aspheric mirrors are used to build a system to enlarge the field of view of a telescope which uses a spherical primary mirror. Field dependent aberration performance can be used to check the alignment status.

9195-15, Session 4

Ambient optomechanical alignment and pupil metrology for the flight instruments aboard the James Webb Space Telescope

Phillip Coulter, Jeffery S. Gum, Theodore J. Hadjimichael, Jason E. Hylan, Timothy J. Madison, Raymond G. Ohl IV, Jerrod Young, NASA Goddard Space Flight Ctr. (United States); Joseph E. Hayden, Sigma Space Corp. (United States); Patrick K. Williams, SGT, Inc. (United States); Kyle F. McLean, Gregory W. Wenzel, Joseph C. McMann, Kevin W. Redman, QinetiQ North America (United States); Maurice Te Plate, European Space Agency (France); Susann Hummel, Markus Melf, Andreas Rödel, EADS Astrium (Germany); Michael Maszkiewicz, Canadian Space Agency (Canada); Alexander Beaton, COM DEV Canada (Canada); Paul F. Schweiger, Lockheed Martin Space Systems Co. (United States); Martyn Wells, David Lee, UK Astronomy Technology Ctr. (United Kingdom)

This talk is about the ambient optomechanical alignment and pupil metrology for the flight instruments aboard the James Webb Space Telescope.

9195-16, Session 4

Integration, alignment, and verification of optical system assembly for FORMOSAT-5

Ching-Wei Chen, Po-Hsuan Huang, Chia-Ray Chen, National Space Organization (Taiwan); Chia-Yen Chan, Chun-Chieh Lien, Po-Han Huang, Ming-Ying Hsu, Shenq-Tsong Chang, Ting-Ming Huang, Instrument Technology Research Ctr. (Taiwan)

FORMOSAT-5 consists of a spacecraft bus and an electro-optical payload. The payload is an f/8 Cassegrain type telescope with 3.6-m effective focal length. The spacecraft has a ground sampling distance of 2-m for panchromatic and 4-m for multispectral bands, with a 24-km swath width. FORMOSAT-5 is the first space program that National Space Organization (NSPO) takes full responsibility for the complete satellite and payload system engineering. The optical system assembly (OSA) has been successfully aligned and is now undergoing final performance verification tests at system level. To help create this unique instrument, NSPO has developed the computer aided alignment assisted with the mechanical ground support equipments to help the assembly, alignment, and verification of the complex systems. This method offers an integrated capability for interferometric alignment and characterization of the large instrument. A detail OSA integration and verification steps, including primary mirror, secondary mirror, corrector lens and baffles alignment are presented. This paper describes the overall capability of this method and uses decomposed Zernike polynomials from the alignment and characterization of the OSA to verify the reduction of the wavefront errors and misalignments. It further demonstrates the successful completion of the instrument and satisfaction with the main system requirements.

9195-17, Session 4

Aberration analysis and calculation in system of Gaussian beam illuminates lenslet array

Zhu Zhao, Mei Hui, Beijing Institute of Technology (China); Ping Zhou, Tianquan Su, The Univ. of Arizona (United States); Yun Feng, Yuejin Zhao, Beijing Institute of Technology (China)

Low order aberration was founded when focused Gaussian beam imaging at Kodak KAI-16000 image detector, which is integrated with lenslet array. Effect of focused Gaussian beam and numerical simulation calculation of the aberration were presented in this paper. First, we set up a model of optical imaging system based on previous experiment. Focused Gaussian beam passed through a pinhole and was received by Kodak KAI-16000 image detector whose micro lenses of lenslet array were exactly focused on sensor surface. Then, we illustrated the characteristics of focused Gaussian beam and the effect of relative space position relations between waist of Gaussian beam and front spherical surface of micro lenses to the aberration. Finally, we analyzed the main element of low order aberration and calculated the spherical aberration caused by lenslet array according to the results of above two steps. Our theoretical calculations shown that the conclusion gave a good agreement with experimental result when front surface of micro lenses is placed just behind the waist of Gaussian beam. Our research results proved that spherical aberration was the main element and made up more than 75.06% of the 48 nm error, which was demonstrated in previous experiment. The spherical aberration was inversely proportional to the value of divergence angle of Gaussian beam and directly proportional to the focal length or thickness of micro lens.

9195-18, Session PMon

Estimation of optical misalignment using artificial neural networks

Lucimara C. N. Scaduto, Opto Eletrônica S.A. (Brazil) and Univ. de São Paulo (Brazil); Mario A. Stefani, Opto Eletrônica S.A. (Brazil); Jarbas C. Castro Neto, Opto Eletrônica S.A. (Brazil) and Univ. de São Paulo (Brazil)

In axially symmetric systems, the third-order aberrations that can be present are spherical aberration, linear coma, quadratic astigmatism, field curvature and cubic distortion. When the axial symmetry is broken due to misalignments, no new aberration forms are generated, but different field-dependent terms of the known ones may occur. This research presents a misalignment estimation method based on the analysis of the wavefront utilizing artificial neural networks. Information about the aberrations in the optical system, which can be described in terms of Zernike polynomials, can be extracted from the transmitted wavefront. Artificial neural networks are employed in the analysis of the coefficients of Zernike polynomials and used to evaluate both type and magnitude of the misalignments. A two-mirror telescope is analyzed and two types of misalignments are considered in this study: tilt and decenter. For two-mirror telescopes, the primary mirror can be considered as a reference and misalignments in the secondary mirror can generate, among other aberrations, linear field-dependent astigmatism and uniform coma. Theoretical misalignments estimated in this optical system are satisfactory when coefficients related to coma and astigmatism are considered.

9195-19, Session PMon

Analysis of a spaceborne mirror on a main plate with isostatic mounts

Chia-Yen Chan, Chun-Chieh Lien, Po-Hsuan Huang, Shenq-Tsong Chang, Ting-Ming Huang, Instrument Technology Research Ctr. (Taiwan)

The paper is aimed at obtaining the deformation results and optical aberration configurations of a spaceborne mirror made of ZERODUR® glass on a main plate with three isostatic mounts for a space Cassegrain telescope. On the rear side of the main plate four screws will be locked to fix the focal plane assembly. The locking modes for the four screws will be simulated as push and pull motions in the Z axis for simplification. The finite element analysis and Zernike polynomial fitting are applied to the whole integrated optomechanical analysis process. Under the analysis, three isostatic mounts are bonded to the neutral plane of the mirror. The deformation results and optical aberration configurations under six types of push and pull motions as well as self-weight loading have been

obtained. In addition, the comparison between the results under push and pull motions with 0.01 mm and 0.1 mm displacements in Z axis will be attained.

9195-20, Session PMon

dynamic mesh-based analysis of irradiance characteristics of solar simulator

Qinglong Meng, Yanpeng Li, Yaxiu Gu, Chang'an Univ. (China)

The unsteady motion of solar simulator was simulated with dynamic mesh technology in software Fluent. The dynamic irradiation characteristics of the simulator under different conditions were studied. Using dynamic layering method achieved mesh update, and using user-defined functions (UDF) defined periodic lifting motion of the simulator. Detail dynamic irradiance was obtained to compare with some experimental results. The results showed that simulator height and the number of light sources were the main factors affecting the irradiance. Irradiance has the linear relation with simulator height, irradiance nonuniformity become smaller with solar height decreasing; Irradiance of various operating conditions meets the superposition of irradiance. The dynamic irradiation numerical results are consistent with experimental results at typical points, which verifies the reliability of the moving mesh numerical model. The validated model can be used to study various conditions and provides forecast data for diurnal variation simulation of solar radiation.

9195-21, Session PMon

Analysis of target wavefront error for secondary mirror of a spaceborne telescope

Shenq-Tsong Chang, Wei-Cheng Lin, Ching-Hsiang Kuo, Chia-Yen Chan, Yu-Chuan Lin, Ting-Ming Huang, Instrument Technology Research Ctr. (Taiwan)

During the fabrication of an aspherical mirror, the inspection of the residual wavefront error is critical. In the program of a spaceborne telescope development, primary mirror is made of ZERODUR with clear aperture of 450 mm. The mass is 10 kg after lightweighting. Deformation of mirror due to gravity is expected, hence uniform supporting measured by load cells has been applied to reduce the gravity effect. Inspection has been taken to determine the residual wavefront error at the configuration of mirror face upwards. Correction polishing has been performed according to the measurement. However, after comparing with the data measured by bench test while the primary mirror is at a configuration of mirror face horizontal, deviations have been found for the two measurements. Optical system that is not able to meet the requirement is predicted according to the measured wavefront error by bench test. A target wavefront error of secondary mirror is therefore analyzed to correct that of primary mirror. Optical performance accordingly is presented.

9195-22, Session PMon

Broadband tunability of femtosecond optical parametric oscillator based on periodically-poled lithium niobate

Tae Young Jeong, Ki-Ju Yee, Chungnam National Univ. (Korea, Republic of)

We demonstrate a broadly tunable femtosecond optical parametric oscillator (OPO) based on MgO doped congruent lithium niobate (CLN) which is synchronously pumped by a Kerr lens mode locked Ti: Sapphire laser. We described on the use of a pair of prims to provide negative group velocity dispersion for compensating the group velocity dispersion. The CLN crystals periodically poled for quasi phase matching with MgO doping of 5.0 mol% has sufficiently reduced photorefraction to allow room temperature operation of the OPO. The pumping pulses have a repetition rate of 87MHz, an average power of 1.8W pulse duration of 100 fs, and the wavelength tunable from 760 nm to 840 nm. The signal wavelength is determined by various parameters such as the poling period, temperature, pumping wavelength and the OPO cavity length. Through optimizing the parameters, we could obtain the signal output being continuously tunable from 1.09 um to 1.60 um by changing the cavity length while other conditions are fixed. The threshold pumping power was 450 mW with the use of BK7 window as broadband output coupler, The maximum signal output power was around 240 mW with 1.8 W pumping, and the pulse duration was measured to be around 100 fs.

9195-23, Session PMon

Gravity effect for the primary mirror assembly of space-borne telescope

Wei-Cheng Lin, Shenq-Tsong Chang, Yu-Chuan Lin, Ming-Ying Hsu, Instrument Technology Research Ctr. (Taiwan)

The purpose of this article investigates the gravity effect of the primary mirror assembly which contains primary mirror, main plate and flexure. Considering mass budget of the investigated 450 mm clear aperture space-borne telescope, the primary mirror is lightweighted with hexagon cell structure scheme about 50 %. For the mirror support mechanism, the flexure has been extensively adopted in various applications such as telescope and lithography projection lens. To achieve the desired optical performance for the optical system, the mounting position of the flexure shall cross through center of gravity of the mirror to prevent the imagine degradation from gravity effect, especially for the lightweight mirror. In this article, the mounting position of the flexure is analyzed by the analytical FEA modeling. Furthermore, the assembly process of this mirror aiming to reduce the astigmatism caused from the gravity effect, bonding process and the deformation from the mounting to the main structure of the telescope (main plate) is proposed. The interferometric test data after primary mirror assembly is also compared to the analytical FEA modeling with the gravity sag.

9195-24, Session PMon

Dynamic compensation for the lithographic object lens

Hongwei Zhu, Tingwen Xing, Institute of Optics and Electronics (China); Zexiang Chen, Univ. of Electronic Science and Technology of China (China)

The nominal design residual aberrations are very small for the lithographic object lens. The RMS wavefront error is in a few milliwaves, and the distortion is in a few nanometers. However, The manufacturing-induced aberrations are inevitable and usually many times larger than the design residual level. One method to reduce the manufacturing-induced aberrations is making a few lens adjustable after the object lens is assembled. Dynamic compensation can correct element metrology and assembly errors effectively, especially for the low order Zernike aberrations. We introduce a dynamic compensation method in this paper. This technique is based on the simulated imaging performance using Zernike sensitivity, which is the simulated results of wavefront aberration change by lens element position change. We can select the potential moving lens by this technique. This method can find the optimum combination of moving lens position where the lithographic object lens imaging performance is improved remarkably.

Conference 9196: Systems Contamination: Prediction, Control, and Performance

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9196-1, Session 1

Standards activity for contamination control at ASTM and IEST

Jack T. Sanders, ATK Space Systems (United States)

The paper will discuss recent work at ASTM and IEST to update existing standards and introduce new standards. The discussion will deals specifically with standards that address contamination control issues. Committee work on standards of interest to contamination control engineers will be discussed. IEST-STD-CC1246E was released in the last year, and changes from revision D will be highlighted. A new ASTM Standard Practice for Spacecraft Hardware Thermal Vacuum Bakeout will also be emphasized.

9196-3, Session 1

Surfaces that shed dust: Unraveling the mechanisms

Genevieve Devaud, Christina Haley, Christina Rockwell, Alex Fischer, Ball Aerospace & Technologies Corp. (United States)

Control of adhesion of particles to surfaces has wide ranging importance, from xerography to contamination control for optics/semiconductors on Earth, to mission-limiting adhesion of lunar dust to spacesuits on the Moon. Removal of small dust particles is well known to be difficult, often requiring mechanical removal. We have developed an ion-beam process (STAR: Surface Treatment Adhesion Reduction) which significantly reduces the adhesion of sub-50 micron particles from Kapton, quartz and silicon surfaces, representing typical materials used in the aerospace industry. In a dry environment, such as a clean room, adhesion of small particles is mediated predominantly by van der Waals or Coulombic interactions. In turn, van de Waals interaction is dependent on the dielectric properties of the material and by spacing loss. Independent of starting material and roughness, the STAR treatment creates a finely textured surface morphology that reduces contact area and increases separation. Advancing contact angles and much increased hysteresis also support an increase in surface heterogeneity. Contact charge transfer was reduced between STAR surfaces and dust particles for silicon surfaces, but not black Kapton, indicating that reduced Coulombic interaction is not required for adhesion reduction. The physical basis of the dust mitigating properties of these modified surfaces is primarily due to nanometer scale topographical differences between STAR and virgin surfaces.

9196-4, Session 1

Analysis of particulates on tapelift samples

De-Ling Liu, Robert M. Moision, John A. Chaney, Chris J. Panetta, The Aerospace Corp. (United States)

Particle counts on tapelift samples taken from a hardware surface exceeded a threshold requirement six times despite successive cleaning. After the tape was switched to a different type, the particle counts were lower and the requirement was met. However, questions were raised regarding tapelift samples handling and processing. The goal of this investigation is to explore the plausible root cause for the tapelifts data anomaly.

Three hardware tapelift and two blank tapelift samples were used in this study. Scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX), and time-of-flight secondary ion mass spectroscopy (ToF-SIMS) were employed to perform chemical composition analysis on the particulates collected on the samples. As revealed in the SEM/EDX results, the common presence of mineral contents on both blank and hardware tapelift samples suggests that environmental dust fallout may play a role. In addition, SEM/EDX identified considerable Na and S containing particles on the hardware samples. This observation led to the use of ToF-SIMS to further examine the Na and S containing particulates via their molecular ion fragments, confirming the presence of sodium alkylbenzene sulfonates. Sodium alkylbenzene sulfonates are common surfactants used in industrial detergents. Thus, it appears that the Na and S containing particulates could have been the detergent residues left behind on the glass slides used to support the tape after the tapelift sampling has occurred, and originated neither from the tape nor from the hardware.

In summary, the investigation suggests that the "out-of-family" particle counts on the tapelift samples may have been attributed to the process of glass slide cleaning and tapelift sample handling.

9196-5, Session 2

Experimental measurement of the reflection behavior of contaminant molecules

Susumu Baba, Eiji Miyazaki, Yuka Miura, Junichiro Ishizawa, Yugo Kimoto, Takashi Tamura, Riyo Yamanaka, Osamu Numata, Japan Aerospace Exploration Agency (Japan)

Spacecraft projects must control the amount of molecular contaminants on the critical surface below specified level determined by mission analysis over the lifetime of the spacecraft. The amount of molecular contaminants on the critical surface, as predicted by the contamination analysis tool, is one of the most important contamination-control information. JAXA is developing a contamination analysis tool "J-SPICE" (Japanese Spacecraft Induced Contamination analysis software). Generally speaking, contamination analysis tools predict the amount of molecular contaminants on critical surfaces based on various input data (outgassing property of materials, geometry of spacecraft, thermal property of spacecraft, etc.) and mathematical models showing the behavior of contaminants (outgassed molecules from materials, transport of outgassed molecules from one surface to another, and molecules adhering to surfaces). Therefore, prediction accuracy is heavily dependent on the validity of mathematical models. However, verification of validity of mathematical models is usually very difficult. Recently, we have verified the validity of the diffuse reflection model applied in J-SPICE among other mathematical models by comparing the reflection flux of contaminant molecules measured by the ground experiment and the analytical result of the J-SPICE. For the ground experiment, we developed equipment with a cold shroud, outgassing source, mirror and QCMs in a vacuum chamber. We also analyzed various ground experiment input data, including a geometrical model of the equipment. The study result showed that a diffuse reflection model of J-SPICE reasonably explain molecules reflection by a flat surface.

9196-6, Session 2

Diffusion of water into purged volumes

Lubos Brieda, Particle In Cell Consulting, LLC (United States); Gregory Bennett, ASRC Federal Space and Defense (United States)

In this paper we report on an experimental and numerical effort to characterize diffusion of atmospheric water vapor into a cavity purged with dry GN2. We investigate the effect of the gas flow rate as well as the inlet aperture aspect ratio. Numerical data is compared to simulation results.

9196-7, Session 2

Identification of collected volatile condensable material from ASTM E595 of silicone damper fluid

Myriam P. Easton, Aura C. Labatete-Goeppinger, Jesse D. Fowler, De-Ling Liu, The Aerospace Corp. (United States)

Polydimethylsiloxane damping fluids used for structural deployment mechanisms are not required to be low outgassing. During normal use, these damping fluids are typically encapsulated; however, an unintentional leak may occur which would cause an undesirable contamination at the leak point and form volatile condensable that could reach contamination sensitive surfaces, degrading the performance of satellites. The collected volatile condensable material (CVCM) at 25°C from ASTM E595 of a damping fluid, MeSi-300K, was > 0.10%, when damping fluid maintained at 125°C for 24 hours, under 10-6 Torr vacuum. MeSi-300K viscosity is 300,000 cs, which indicates an average molecular weight (MW) of 204,000 daltons. This large MW polymer would contain about 2,756 dimethyl siloxane (DMS) units in the chain. These long chains are not expected to be volatile; however, during manufacture, linear chains and cyclic compounds of smaller number of DMS units are produced that are volatile.

Gas chromatography mass spectrometry (GC-MS) was used to identify the CVCM material. Characterization of these materials revealed that the CVCM contained MW siloxanes, straight chain and cyclic, in the range of 10 to 16 DMS units, whereas, CVCM from space-qualified silicone based materials have 3 to 7 DMS units. Consequently, contamination from MeSi-300K material would produce greater amounts and higher MW siloxanes than space-qualified silicones. These higher MW species would be harder to remove by evaporation and could remain on sensitive surfaces.

9196-8, Session 3

Molecular transport modeling for spaceborne instrument contamination prediction

Chung M. Wong, Robert M. Moision, Jesse D. Fowler, De-Ling Liu, The Aerospace Corp. (United States)

We present a finite element model for the prediction of molecular contamination of hypothetical spaceborne assets in the molecular flow regime using the commercially available COMSOL Multiphysics software. The model is an alternative to the typical Monte Carlo method in that it assumes molecules are first adsorbed onto a surface and subsequently diffusely emitted from the surface. Dependent variables near the boundaries are derived through kinetic theory using input parameters such as temperature, desorption rate, and sticking coefficient that are assigned to each wall. The transport of molecules onto a boundary wall is computed by integrating fluxes arriving from all other surfaces in its line of sight. Results from the finite element model are validated by comparison to experimentally derived transport properties of molecules through similar mechanical structures. These mechanical structures contain narrow tortuous pathways that allow contaminants to slowly migrate into a spaceborne instrument and possibly cause performance degradation. The characteristic size of these pathways reflects those that are commonly found in spaceborne optomechanical structures. Results from the model are further verified through Monte Carlo methods that simulate molecular transport through simple structures. The rate of growth of ice films on low temperature optical components and their optical performance degradation will be discussed in this paper.

9196-9, Session 3

Analysis of molecular conductance through a labyrinth vent

Lubos Brieda, Particle In Cell Consulting, LLC (United States); Tim Gordon, SGT, Inc. (United States)

Spacecraft instruments typically utilize labyrinth vents to depressurize internal cavities during exposure to reduced pressure environments. Although nominally the flow through the vents is from the inside to the outside, during thermal vacuum testing such vents can permit transport of molecular contaminants from the vacuum chamber to the sensitive internal optics. In this paper, we use numerical techniques to analyze the conductance through labyrinth vents and use it to derive allowed molecular fluxes to the instrument external surfaces.

9196-10, Session 3

Evaluating the bakeout effectiveness of RTV-S691 silicone adhesive by measuring outgassing rate

Eiji Miyazaki, Yuka Miura, Osamu Numata, Riyo Yamanaka, Susumu Baba, Junichiro Ishizawa, Yugo Kimoto, Takashi Tamura, Japan Aerospace Exploration Agency (Japan)

The Japan Aerospace Exploration Agency, JAXA, has maintained a facility capable of measuring outgassing rates since 2010. Outgassing rate measurements are basically performed for fresh materials, e.g. just cured adhesives, paints, etc. and reveal a lot about how the material can behave as a contamination source. As we know, bakeout is one of the key techniques used to reduce contaminant emissions from materials. In the design phase of a spacecraft, particularly for contamination-critical missions, it is important to determine the bakeout process sufficiently, or we will be unable to estimate the reduction level of contamination in orbit for years. Accordingly, we attempted to measure the outgassing rate of already baked-out material samples to evaluate the bakeout effectiveness. In the present study, a typical silicone adhesive for use in space, RTV S-691, Wacker Chemie, was selected for the measurement. The cured sample, with dimensions of 40 ? 40 ? 3.5 mm, was applied for two-time isothermal tests under identical conditions: 125 degrees C for 144 hours. The first test is also used as a bakeout at 125 degrees C for 144 hours. In other words, the second test involved measuring the baked-out sample. Consequently, the outgassing rate curve was apparently reduced as expected. In addition, some findings in the outgassing rate curve were also observed. The details of the evaluation results, based on outgassing rate data, will be presented and discussed at the conference.

9196-11, Session 3

quantitative model of the effects of contamination and space environment on in-flight aging of thermal coatings

Emilie Vanhove, Jean-François Roussel, ONERA (France); Stéphanie Remaury, Delphine Faye, Pascale Guigue, Ctr. National d'Études Spatiales (France)

The in-orbit aging of thermo-optical properties of thermal coatings such as mirrors or paints critically impacts both spacecraft thermal balance and heating power consumption. Nevertheless, in-flight thermal coating aging is generally larger than the one measured on ground and the current knowledge does not allow making reliable predictions. As a result, a large oversizing of thermal control systems is required. To address this issue, the Centre National d'Etudes Spatiales has developed a low-cost experiment, called THERME, which enables to monitor the in-flight time-evolution of the solar absorptivity of various coatings, including commonly used coatings and new materials by measuring their temperature. This experiment has been carried out on sun-synchronous spacecrafts for 27 years, allowing thus the generation of a large set of telemetry measurements.

The aim of this work was to develop a model able to quantitatively reproduce these in-flight data with a restraint number of parameters.

The underlying objectives were to better understand the contribution of the different involved phenomena and later on to predict the thermal coating aging at end of life. The physical processes modeled include contamination deposition, UV aging of both contamination layers and intrinsic material and atomic oxygen erosion. Efforts were particularly focused on the satellite leading wall as this face is exposed to the highest variations in environmental conditions during the solar cycle. The non-monotonous time-evolution of the solar absorptivity of thermal coatings is shown to be due to a succession of contaminants deposits and contamination erosion by atomic oxygen phased with the solar cycle.

9196-12, Session 4

Towards high-fidelity simulations of multiple thruster plumes for contamination prediction

Hiroumi Tani, Japan Aerospace Exploration Agency (Japan); Tetsufumi Ohmaru, Ryoyu Systems Co., Ltd. (Japan); Naoki Isobe, Takao Nakagawa, Japan Aerospace Exploration Agency (Japan)

Satellites and rockets on the orbits often exhaust gas plumes from chemical thrusters, propellant tanks and optical cooling systems. The gas plumes largely expand into the space vacuum, and they may impinge on the optical devices and the spacecraft bodies and cause significant problems, such as contamination, heat loads, disturbance force and torque. Semi-theoretical models, e.g. a point-source model, are conventionally used to predict such gas plumes under the assumption that the source of gas plume is single. However, spacecraft often fire multiple thrusters for the attitude control, and the interaction between the multiple plumes influences the plume expansion and the impingement on spacecraft bodies. In the present study, the effects of multiple thruster plumes upon the plume expansion and the impingement on spacecraft were investigated from the perspective of the contamination prediction. A hybrid Navier-Stokes (NS)/Direct Simulation Monte Carlo (DSMC) technique was employed for a high-fidelity simulation of multiple rarefied plumes. The present technique was validated by comparing to the computational data of single and dual plumes in rarefied conditions. Further, the applicability of the point-source model to multiple thruster plumes was also explored. It was found that the present high-fidelity method has a significant advantage of accurately estimating the gas molecular distributions of the multiple plumes. Finally, the simulations of multiple thruster plumes of the next-generation infrared space telescope SPICA are presented as one of the successful examples of mission-risk mitigation by the high-fidelity simulations.

9196-13, Session 4

Ozone Mapping and Profiler Suite: Using mission performance data to refine predictive contamination modeling

Genevieve Devaud, Ball Aerospace & Technologies Corp. (United States); Glen Jaross, NASA Goddard Space Flight Ctr. (United States)

Molecular transport modeling is routinely used to predict optical throughput changes due to contaminant accumulation to ensure performance margin to EOL; the results also drive cleanliness requirements, which have large cost implications. The geometry, thermal profile and material properties must be accurately modeled in order to have confidence in the results, yet it is well known that the complex chemistry and process dependent variability of aerospace materials presents a substantial challenge to the modeler. Assumptions about the desorption kinetics of BOL non-volatile residues, and the diffusion kinetics of outgassing species from polymeric materials, dramatically affect the model results, yet it is rare indeed that on-mission data is analyzed at a later date as a means to challenge, or confirm, the modeling results. The time dependence of the contaminant thickness is an important output of a transport model. Coupled with absorption coefficients and Beer's Law, one could then predict the time dependence of optical throughput losses. Happily, measurements are available for the Ozone Mapping Profiler Suite on the Suomi NPP Satellite, which launched October 28, 2011; optical throughput degradation between day 145 and day 670 is less than 1%. We will show how assumptions about outgassing rates and desorption energies, in particular, dramatically affect the modeled outcome in terms of the expected contaminant thicknesses and time dependence.

9196-16, Session 5

Spacecraft materials HCl susceptibility assessments

Chung-Tse Chu, De-Ling Liu, Hyun I. Kim, Diana R. Alaan, The Aerospace Corp. (United States)

Potential hydrogen chloride (HCl) corrosion of spacecraft materials is a concern for space launch operations and various space programs in over-flight scenarios associated with Evolved Expendable Launch Vehicles (EELV). Over-flight refers to the circumstance where one spacecraft, resident on a launch pad, may be exposed to HCl generated from solid rocket boosters in an earlier launch operation at an adjacent pad. Under unfavorable meteorological conditions, HCl vapor in the rocket plume can migrate in the atmosphere, and subsequently be ingested into the payload fairing (PLF) for the spacecraft still on the pad. One aspect of the over-flight risk assessments involves spacecraft materials susceptibility to HCl exposure. In our investigation, laboratory testing was performed to gain insights into potential performance degradation of spacecraft materials due to HCl exposure. A wide range of spacecraft materials, including thermal control coatings, sun shields, optical solar reflectors, solar cell coverglasses, metal contacts, and a gold plated mirror were exposed to HCl vapor in a well-characterized facility. Sample thermal/optical and electrostatic dissipation properties, as well as surface chemical and morphological features, were characterized before and after the HCl exposure. All materials tested showed no significant degradation with HCl exposure dosages of 500 ppb-hr, which is considered as a conservative upper bound in the EELV over-flight scenario. These results helped the establishment of the technical rationale that properly charcoal-filtered air as the PLF purge should pose little risk in terms of HCl contamination under EELV over-flight scenarios.

9196-17, Session 5

Black molecular adsorber coatings for spaceflight applications

Nithin S. Abraham, Mark M. Hasegawa, Sharon A. Straka, NASA Goddard Space Flight Ctr. (United States)

The molecular adsorber coating is a new technology that was developed to mitigate the risk of on-orbit molecular contamination on spaceflight missions. The application of the coating would be ideal near sensitive interior surfaces and instruments that are often targeted by outgassed materials, such as plastics, adhesives, lubricants, epoxies, tapes, and potting compounds. Sensitive surfaces may include optics, electronics, detectors, and thermal control surfaces. This sprayable paint technology is comprised of inorganic white materials made from highly porous zeolite. In addition to good adhesion performance, thermal stability, and adsorptive capability, the molecular adsorber coating offers favorable thermal characteristics. However, low reflectivity properties, which are typically offered by black coatings, are desired for some spaceflight applications. For example, black thermal control coatings are used on interior surfaces, in particular, on baffles for optical straylight control. Similarly, they are also used within light paths between optical systems, such as telescopes, to absorb light.

Recent efforts have been made to transform the white molecular adsorber coating into a black coating. This result is achieved by optimizing the current formulation with black pigments while still maintaining the adsorptive properties of the coating for outgassing control. Different binder to pigment ratios, coating thicknesses, and spray

application techniques were explored to develop a black version of the molecular adsorber coating. During the development process, coating performance and adsorption characteristics were studied. Preliminary work performed on black molecular adsorber coatings thus far is very promising. Continued development and testing is necessary for its use on future contamination sensitive spaceflight missions.

9196-18, Session 5

Optical characterization of photofixed RTV effluent in an atomic oxygen atmosphere

Natale J. Ianno, Jinya Pu, Univ. of Nebraska-Lincoln (United States)

It is well know that the elevated satellite operating temperature causes the unused catalyst material in the Room Temperature Vulcanized materials (RTV) to volatize, which can then re-deposit or condense onto other spacecraft surfaces. In the presence of sunlight, this Volatile Condensable Material (VCM) can photo-chemically deposit onto optically-sensitive spacecraft surfaces and significantly alter their original, beginning-of-life (BOL) optical properties, such as solar absorptance and emittance, causing unintended performance loss of the spacecraft. This has been studied in vacuum environments simulating geosynchronous orbits, but never to our knowledge in atomic oxygen environments simulating low earth orbit. In view of this we have added an effusion cell and UV light source to our existing atomic oxygen system and will present the optical properties of photofixed VCM films generated from DC-93-500, SCV-2590 and SCV-2590-2. We will employ ex-situ spectroscopic ellipsometry to extract n and k of the films as a function of wavelength. These results can be compared to the previously obtained optical constants of photofixed films deposited in a vacuum environment, allowing the effect of atomic oxygen on the film properties to be quantified.

9196-19, Session 5

Optical and re-emission behavior of silicone contaminants effected by UV irradiation with different wavelength ranges

Yuka Miura, Susumu Baba, Riyo Yamanaka, Eiji Miyazaki, Junichiro Ishizawa, Yugo Kimoto, Takashi Tamura, Japan Aerospace Exploration Agency (Japan)

Molecular contamination by outgassing, released from a spacecraft can degrade the performance of optical components, the thermo-optical properties of thermal control surfaces, and power output generated by a solar array. To restore the performance, one typical method involves eliminating the contamination from the surface, for which thermal heating baking is commonly used. Accordingly, understanding the re-emission behavior of molecular contaminants is crucial to determine the minimum heating temperature and duration required. However, we should also consider the space environment in orbit, e.g. UV, AO, etc. Among such environmental factors, UV is one of the most critical. There is a possibility that it cuts the chains of organic molecules in contaminants due to its high energy, degrading optical properties, even in change of re-emission behavior. For instance, while in orbit, UV beams have various wavelengths. Short wavelength beams are low-intensity but high-energy, so the effect of wavelength must be understood. In the present study, using two kinds of UV sources with different wavelength ranges, we compare the effect from UV lights irradiated on an optical surface with silicone contaminants. We have used silicone adhesive as an outgassing source, because it is widely used in spacecraft. The irradiated samples were evaluated in terms of their optical properties and re-emission behavior, i.e. transmittance, and thermal desorption. We also investigated the VUV and UV irradiation effect of silicone contaminants. Compared to VUV and UV irradiation, the trend toward the VUV shows a short wavelength with a large effect observed, even in terms of its re-emission behavior.

9196-20, Session 5

Effects of Ni diffusion on gold plated mirrors

David P. Taylor, Chung-Tse Chu, The Aerospace Corp. (United States)

Gold-coated mirrors are widely used in infrared optics for industrial, space, and military applications. These mirrors are often made of aluminum or beryllium substrates with polished nickel plating. Gold is deposited on the nickel layer by either electroplating or vacuum deposition processes. Atmospheric corrosion of gold-coated electrical connectors and contacts was a well-known problem in the electronic industry and studied extensively. The changes of optical properties of the gold mirrors were correlated to the morphology of corrosion features on the mirror surface.

9196-21, Session 5

Investigation of laser induced damage performance of optical coatings in vacuum environment

Meiping Zhu, Kui Yi, Shanghai Institute of Optics and Fine Mechanics (China); Xiulan Ling, North Univ. of China (China); Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China)

The ZrO2 monolayer coating, SiO2 monolayer coating, as well as the multilayer coating consisted of ZrO2 and SiO2 layers have been deposited, using traditional e-beam evaporation technique. The damage performance of prepared dielectric coatings induced by 1064 nm nanosecond pulse irradiation in atmosphere environment, vacuum environment and special atmosphere environment was investigated and compared. Thermal-mechanical damage mechanism and defect induced damage mechanism were employed to analysis the intrinsic damage mechanisms of porous films in vacuum environment. In addition, the impact of the organic contaminations, as well as the longtime outgassing organic contaminations in vacuum environment on the laser induced damage threshold has been studied.

9196-22, Session 6

Contamination control requirements implementation for the James Webb Space Telescope (JWST), part 1: optics, instruments and thermal vacuum testing

Eve M. Wooldridge, NASA Goddard Space Flight Ctr. (United States); Kelly Henderson-Nelson, Michael S. Woronowicz, Kevin Novo-Gradac, Radford L. Perry III, SGT, Inc. (United States); Matthew Macias, Northrop Grumman Aerospace Systems (United States); Joanne Egges, Ball Aerospace & Technologies Corp. (United States)

The derivation of contamination control requirements for JWST was presented at the SPIE conference in 2008. Since then, much work has been done to allocate contamination at each phase of Integration and Test (I&T) and to plan for achieving the allocations. Because JWST is such a large and complicated observatory, the plans are many and varied. There are primary mirror segments that must be cleaned early and maintained clean; there are 4 science instruments that each have tight contamination requirements but cannot be cleaned after they are integrated onto the Integrated Science Instrument Module (ISIM) structure; there is the composite ISIM structure that is fragile and must be minimally handled; there are numerous cryo-vacuum tests that must be controlled and monitored in order to minimize molecular contamination during return to ambient; … and more. An overview of plans developed

to implement contamination control for JWST optics, instruments, and thermal vacuum testing for JWST will be presented.

9196-23, Session 6

Contamination control requirements implementation for the James Webb Space Telescope (JWST), part 2: spacecraft, sunshield, observatory, and launch

Eve M. Wooldridge, Nithin S. Abraham, NASA Goddard Space Flight Ctr. (United States); Kelly Henderson-Nelson, Michael S. Woronowicz, SGT, Inc. (United States); Matthew Macias, Northrop Grumman Aerospace Systems (United States); Olivier Schmeitzky, Peter Rumler, European Space Research and Technology Ctr. (Netherlands); Jacques Breton, Beatriz Romero, Bruno Erin, Arianespace (France)

This paper will continue from Part 1 of JWST contamination control implementation. In addition to optics, instruments, and thermal vacuum testing, JWST also requires contamination control for a spacecraft that must be vented carefully in order to maintain solar array and thermal radiator thermal properties; a tennis court-sized sunshield made with 1-2 mil Kapton layers that must be manufactured and maintained clean; an observatory that must be integrated, stowed and transported to South America; and a rocket that typically launches commercial payloads without contamination sensitivity. An overview of plans developed to implement contamination control for the JWST spacecraft, sunshield, observatory and launch vehicle will be presented.

Conference 9197: An Optical Believe It or Not: Key Lessons Learned III

Monday 18–18 August 2014

Part of Proceedings of SPIE Vol. 9197 An Optical Believe It or Not: Key Lessons Learned III

9197-1, Session 1

Two to the sixth and counting: a lifetime of optical experiences in five parts *(Keynote Presentation)*

James W. Mayo III, Tau Technologies LLC (United States)

This presentation will cover 64 years of experience with telescopes, optical components, optical coatings, large optics, optical fabrication, lasers and related subjects. It will focus on five topic areas paying special attention to critical lessons learned in these areas. Part 1 will cover contributions and inherent value of mentoring in optical and astronomical sciences. This will include specific personal experiences and valuable lessons learned from teachers and mentors going back to the beginning of the space age and the first satellites. It will also cover selected examples from the author's mentoring and community optics and astronomy outreach efforts. Part 2 will delineate the lessons learned from the investigation and independent expert review and assessment of optical damage incidents over a period of five decades. It will also recount frequent optical misconceptions that have negatively impacted efficient system development and implementation over the years and how to avoid them. Part 3 will consist of a short tutorial on the tools, techniques, and the "how and why" of optical inspection. This will be interlinked with the previous optical damage and mistakes topic, where possible. Part 4 will consist of the author's involvement and experiences in optical education with emphasis on the founding and early years of the University of Arizona Optical Sciences Center, now the College of Optical Sciences. Part 5 will cover the enduring issues and challenges for managers, planners and contributing scientists for large optics and telescope projects. This brief overview will follow up and expand upon the author's presentation on this topic at the 1985 "SPIE Optical Fabrication and Testing Workshop: Large Telescope Optics", Albuquerque, NM. Throughout all topic areas presented, the author will stress the lessons learned and the value of these lessons to the planning, management and successful execution of future optics projects and programs.

9197-2, Session 1

Timing is the elusive connector of dreams *(Invited Paper)*

Joe J. Lones, Adroit Engineering, Inc. (United States); Lance Lones, eHoncho Ltd. (United States)

SPIE Fellow Joe Lones and son, Lance Lones, offer a somewhat historical view of early SPIE activity, and an entertaining chronicle of some lessons learned. Tradition requires attendees to attempt separating fact from embellishment of various trivia including establishing San Diego as a venue for the SPIE Annual Meeting under the imagination of Joe Yaver and some Southern California members.

9197-3, Session 2

Perspective on new technology product introduction *(Invited Paper)*

Douglas A. Kirkpatrick, InnerProduct Partners (United States)

No Abstract Available

9197-4, Session 2

Bumps in the road *(Invited Paper)*

James B. Breckinridge, Breckinridge Associates, LLC (United States) and College of Optical Sciences, The Univ. of Arizona (United States) and California Institute of Technology (United States)

No Abstract Available

9197-5, Session 2

Lessons learned from starting Rochester Precision Optics *(Invited Paper)*

William P. Hurley, Rochester Precision Optics, LLC (United States)

No Abstract Available

9197-6, Session 2

Use it or lose it: a survey of winning and losing in new optical product development

Alson E. Hatheway, Alson E. Hatheway Inc. (United States)

"There is a tide in the affairs of men which taken at the flood leads on to fortune. Omitted, all the voyage of their life is bound in shallows and in miseries." -- W. Shakespeare

9197-7, Session 3

Learning from near-misses to avoid future catastrophes *(Invited Paper)*

Robin L. Dillon-Merrill, Georgetown Univ. (United States)

Complex projects are forever going to be plagued by performance ambiguity. The challenge for project managers is to be able to identify problems that could be catastrophic, but currently emit only weak signals. The challenge is further magnified when these weak signals persist over time. Such recurrence of an anomaly with no obviously bad outcome can create the false impression of system safety. For example, on the Mars Climate Orbiter (MCO) mission, despite the need for numerous course corrections all the way to Mars (i.e., weak signals), it was never considered that the programming might be suspect until the spacecraft was lost while trying to enter orbit around Mars. Even when signals are more obvious (O-ring failure or foam shedding), when repeatedly observed, the ability to interpret these events as anomalies (and hence report them as such) commonly decreases over time because near-misses are often categorized as successes (the so-called "near-miss bias") (Dillon & Tinsley, 2008) and because of normalization of deviance (Vaughan, 1996). Unfortunately, near-miss recognition only increases again if hazards are made salient by the occasional large failure. This presentation will discuss prescriptions for project managers to recognize and improve organizational learning from near-miss events.

9197-8, Session 3

Managing human fallibility in critical aerospace situations *(Invited Paper)*

Larry Tew, Ctr. for Error Management (United States)

Great care is needed to handle the critical optics without incident or damage, and this is especially true for meter-class mirrors. We report on the highly successful experience of fabricating the JWST mirror suite at L-3 Integrated Optical Systems in Richmond California (Tinsley). Due to the significant number of mirrors, and the large number of operations each mirror receives, 336,000 “opportunities” to damage or destroy a mirror were identified including many repetitious and monotonous operations. The initial manufacturing plan recognized risks, and this was reflected in significant investment toward all aspects of fixtures for handling and storage, and in the design of the machines used for optical finishing and metrology. We expected a very low error rate, and a very low error rate by any industry standard was observed even at the onset of optical fabrication. Yet due to the critical path status of this Program Element, and the unacceptably high cost associated with damage to or loss of mirror segments, any anomaly to work instructions, including unexpected outcomes of a process, required reporting and comprehensive analysis of cause and corrective action. While at the onset of fabrication the anomalies were substantially at a lower level than industry expectations, a decision was made to address human frailty differently, and The Program was stopped for two months. A change of both procedures and culture was implemented during this period. The result was remarkable. The anomaly rate dropped by a factor of 20 from the already good record at start, and remained at that low level throughout the remainder of the Optical Finishing Element of the JWST build. All mirrors were finished to specification. We will discuss the metrics and methods used, and the relevance and benefits of what was done here to other mid-scale production programs involving delicate, high-value mission-critical components.

9197-9, Session 3

Sound bites: A discussion on lessons learned from the integration of space sensors

Catherine D. Merrill, The Univ. of Arizona (United States)

No one sets out to be a bad manager, most people go into engineering don’t want to be a manager at all. Those of us that grow into a management and/or lead role want to do it well. All of us, however, have examples of mangers that have fallen short. Anyone who has achieved these roles in the program does not want to be one of those. But how do people do it? In my time in industry, I have collected a series of sound bites that stay with me and guide me through my career. A sound bite is defined as “a brief recorded statement (as by a public figure) broadcast especially on a television news program; also: a brief catchy comment or saying.” These include “Trust but Verify”, “BKSS”, and “Plan the Work; Work the Plan”. Through them, I am reminded of key lessons learned to effective leadership.

9197-10, Session 4

That can’t possibly be right!: Lessons learned in software modeling

Richard N. Pfisterer, Photon Engineering LLC (United States)

No Abstract Available

9197-11, Session 4

History of the formerly top secret KH-9 Hexagon spy satellite

Phil Pressel, Quartus Engineering Inc. (United States)

No Abstract Available

9197-12, Session 4

A smart rock *(Invited Paper)*

Phil Pressel, Quartus Engineering Inc. (United States)

This project was to design a test station for an infrared bullet (the rock). It was so complicated that no company would dare to bid on it and even we at the Perkin-Elmer Corporation in Danbury, Connecticut were unsure whether we could make it work. The rock had to be rotated at 1500 rpm in a vacuum space that was connected to the rest of the in-air rotating assembly and to keep it from wobbling more than 10 micro-radians while feeding it liquid helium at 4 degrees Kelvin and monitoring its dynamic motion using optical techniques. The successful design combined the disciplines of cryogenics and heat transfer, precision optics, precision bearings and high-speed dynamics.

9197-13, Session 4

See evil, hear evil *(Invited Paper)*

Phil Pressel, Quartus Engineering Inc. (United States)

The purpose of this project was to design and fabricate a ground based Cassegrain telescope to provide 90 degree scanning in elevation and +/- 200 degrees in azimuth. It contained several unique features such as: 1. The ability to provide hard stops at each end of azimuth travel greater than 360 degree; 2. Geared motor drives in azimuth and elevation with zero backlash; and, 3. It was required to rotate 11 cables with diameters from .5 to 2.5 inches, going from the stationary base up through a rotating spindle into the elevation yoke thus requiring them to also travel through +/- 200 degrees.

9197-14, Session 4

Stress failure vignettes: errors of 10,000, the help of Humpty-Dumpty, and others

John W. Pepi, L-3 Communications IOS-SSG (United States)

An aircraft window was designed for 10,000 hours of life under extreme environments, consisting of high altitude thermal gradients and high pressure differential. Further, the window would need to survive its lifetime in the presence of airborne dust particles at high speed, runway sand and debris, hailstone impact, and frequent handling and cleaning conditions, the latter of which could cause scratches. Analysis showed a lifetime well in excess of 1,000,000 hours, but tests indicated failure times well below 1000 hours. The apparent disconnect was due to the presence of residual stress, heretofore not considered. Additionally, premature hailstone test failure required further assessment to ensure survivability. An extensive redesign resulted in the first ever FAA approval for glass window design in a passenger cabin.

9197-15, Session 4

How to break a lens

Alan E. DeCew Jr., MIT Lincoln Lab. (United States)

No Abstract Available

9197-16, Session 4

Lessons learned in athermal lens design: you can't always get what you want

John Polizotti, BAE Systems (United States)

No Abstract Available

9197-17, Session 4

Lessons learned: Design, start-up, and operation of cryogenic systems

William M Bell, Richard E Bagley, Stuart Motew, Paul-W Young,
Topsfield Engineering Service, Inc. (United States)

No Abstract Available

Conference 9198: Ultrafast Nonlinear Imaging and Spectroscopy II

SPIE. OPTICS+ PHOTONICS OPTICAL ENGINEERING+ APPLICATIONS

Sunday - Monday 17–18 August 2014

Part of Proceedings of SPIE Vol. 9198 Ultrafast Nonlinear Imaging and Spectroscopy II

9198-1, Session 1

Morpho-chemistry and functionality of diseased biological tissues

Marta Lange, Riga Technical Univ. (Latvia); Riccardo Cicchi, Francesco Pavone, European Lab. for Non-linear Spectroscopy (Italy)

Nowadays one of the most frequent challenges in medicine is early cancer diagnostics.

In this study different types of biological tissue were examined in order to discover the morpho-chemistry and functionality in order to establish a new standard for cancer diagnostics.

The multi-modal microscopy techniques used are:

1) fluorescence lifetime imaging microscopy (FLIM)

2) Raman Spectroscopy

3) Second Harmonic Generation (SHG)

The experimental setup consisted of a custom-made upright non-linear microscope able to perform combined two-photon-excited fluorescence (TPEF) and SHG by detecting emitted photons in proportional regime, and FLIM- multispectral two-photon emission detection (MTPE) by working in single-photon counting regime. [1] FLIM is an additional non-invasive microscopy technique enabling the identification of endogenous fluorescence species by measuring the decay rate of their fluorescent emission. [1] In this study, different tumor lesions with different severity were observed.

Results:

In this work a multidimensional analysis for tissue characterization was used by combining all the non-linear microscopy techniques described above. A morphological analysis was performed by using TPEF and SHG on ex-vivo tissue slices.

Conclusions:

With FLIM and Raman spectroscopy it is possible to provide functional evaluation of the samples. The aim is to observe the correlation between the morphology and functionality of the molecules in the biological tissue. With using the techniques mentioned before, it is possible to discriminate tumor and healthy tissue that is a great step towards a new diagnostic standard.

In conclusion, in this work it is demonstrated that the capability of our multidimensional method to discriminate between healthy tissue and tumor in ex-vivo tissue slices. Both morphological and spectroscopic differences were found between the two tissue types.

References:

[1] R.Cicchi, A. Crisci, A.Cosci,G.Nesi,D.Kapsokalyvas,S.Giancane, M. Carini, and F.S. Pavone "Time- and Spectral-resolved two-photon imaging of healthy bladder mucosa and carcinoma in situ", Optics Express, Vol. 18 Issue 4, pp.3840-3849 (2010).

9198-2, Session 1

The use of one- and two- photon induced fluorescence spectroscopy for the optical characterization of carcinogenic aflatoxins

Lien Smeesters, Wendy Meulebroeck, Stefan Raeymaekers, Hugo Thienpont, Vrije Univ. Brussel (Belgium)

Carcinogenic and toxic contaminants in food and feed products are nowadays mostly detected by destructive, time-consuming chemical analyses, like HPLC and LC-MS/MS methods. However, as a consequence of the severe and growing regulations on food products by the European Union, there arose an increased demand for ultra-fast, high-sensitive and non-destructive detection of contaminants in food and feed products. Therefore, we have investigated fluorescence spectroscopy for the characterisation of the carcinogenic Aflatoxins. With the use of a tunable Titanium-Sapphire laser in combination with second and third harmonic wavelength generation, both one- and two-photon induced fluorescence excitation wavelengths could be generated within the same setup. We characterised and compared the one-photon induced fluorescence signal after excitation with 265nm and 365nm. The two-photon induced fluorescence signal was obtained after excitation with 730nm. Moreover, the fluorescence intensity as function of the excitation power was studied. Afterwards, this characterisation tool was applied to the detection of Aflatoxins in maize samples. The fluorescence spectra of both healthy and contaminated maize samples were experimentally characterised. In contrast to the fluorescence spectra of the pure Aflatoxin powder, an unwanted influence of background fluorescent elements is observed. Depending on the excitation wavelength, a different influence of these background fluorescent elements, like chlorophyll, was obtained. The interpretation of the fluorescence spectra of the different maize samples allowed the identification of the contaminated samples. As a result, this technology can provide a valuable tool for the non-destructive, real-time and high-sensitive detection of Aflatoxins in maize.

9198-3, Session 1

Combined Raman spectroscopy and autofluoresence imaging method for in vivo skin tumor diagnosis

Valery P. Zakharov, Ivan A. Bratchenko, Dmitry N. Artemyev, Oleg O. Myakinin, Samara State Aerospace Univ. (Russian Federation); Sergey V. Kozlov, Alexander A. Moryatov, Samara State Medical Univ. (Russian Federation)

The problem of noninvasive monitoring of human tissues and cancer detection requires innovate diagnosis method with high sensitivity and specificity. In current work we developed a combined Raman spectroscopy and autofluorescence imaging method for skin lesion type determination.

We developed NIR autofluorescence imaging method to observe and characterize the melanin distribution in human skin. This distribution allows us to formulate one of criteria for skin tumors detection, such as malignant melanoma (MM) and pigmented nevi (PN). Also autofluorescence imaging method allows fast skin tumor's boundaries detection.

Raman spectroscopy allows one to determine malignant changes in tissues. Specific peaks were revealed in Raman scattering shifts for tumors sensing with 785 nm laser. More than 60 human skin tissue samples were tested by the combined method. We propose two-step phase method for skin cancer type diagnosis based on the localization changes in the spectral intensity of Raman bands in the 1300-1340, 1430-1460 and 1640-1680 cm-1. At the first step we analysed spectral intensity changes of the Raman bands in 1300-1340 and 1640-1680 cm-1 in relation to the intensity of the 1450 cm-1 in a phase plane. At the second step of the phase method we analysed absolute changes in the intensities of the 1320, 1450, 1660 cm-1 bands of healthy tissue and pathologies in the non-normalized Raman spectra.

For tumors type classification at the phase plane we used Quadratic Discriminant Analysis. Proposed two-step phase method allows to reach 88,9% of sensitivity and 87,8% specificity for in vivo MM diagnosis.

9198-4, Session 1

Polarization spectroellipsometric measurements for ecological monitoring aquatic environment

Ferdenant A. Mkrtchyan, Institute of Radio Engineering and Electronics (Russian Federation)

The creation of multichannel polarization optical instrumentation and use of spectroellipsometric technology are very important for the real-time ecological control of aquatic environment. Spectroellipsometric devices give us high precision of measurements.

This report is aimed to describe: a compact measuring - information multichannel spectroellipsometric system (device) for monitoring the quality of aquatic environment, that is based on the combined use of spectroellipsometry and training, classification, and identification algorithms

This spectroellipsometric system will differ from modern foreign analogues by the use of a new and very promising method of ellipsometric measurements, an original element base of polarization optics and a complex mathematical approach to estimating the quality of a water object subjected to anthropogenic influence.

Unlike foreign analogues, the system has no rotating polarization elements. This allows one to increase the signal-to-noise ratio and the long-term stability of measurements, to simplify and reduce the price of multichannel spectroellipsometers.

The system will be trainable to the recognition of the pollutants of aquatic environment.

A compact measuring - information multichannel spectroellipsometric system (device) is applied for monitoring the quality of natural and waste water, that is based on the combined use of spectroellipsometry and training, classification, and identification algorithms.

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9198-5, Session 2

3-GHz, ultrafast Yb-fiber laser sources: filling spectral gap *(Invited Paper)*

Hung-Wen Chen, Jinkang Lim, Massachusetts Institute of Technology (United States); Shanhui Xu, Zhongmin Yang, South China Univ. of Technology (China); Franz Kaertner, Massachusetts Institute of Technology (United States) and Deutsches Elektronen-Synchrotron (Germany) and Univ. Hamburg (Germany); Guoqing Chang, Massachusetts Institute of Technology (United States) and Deutsches Elektronen-Synchrotron (Germany)

Many applications require GHz femtosecond pulses at the wavelength range that cannot be covered by commercially available lasers. For example, most live biological specimens exhibit a minimum light attenuation in the range of 1.2-1.35 ?m. Using GHz femtosecond pulses of this wavelength range for nonlinear bio-optical imaging allows deeper penetration through turbid specimens and mitigation of photoinduced damage.

We demonstrate a fundamentally mode-locked, femtosecond (~206 fs) Yb-fiber laser with the highest repetition-rate of 3 GHz. With 1-cm heavily Yb-doped phosphate glass fiber as the gain medium and a high-dispersion (-1300 fs2) output coupler for dispersion compensation, the laser self-starts and produces up to 53-mW average power.

With this oscillator seeding a chain of Yb-fiber amplifiers followed by a diffraction-grating based compressor, we obtain ~110-fs pulses with >12-W average power. we demonstrate that a combination of a high power 3-GHz Yb-fiber laser system and fiber-optic Cherenkov radiation provides new capabilities to ultrafast laser technology: generation of ~14 fs pulses with smooth spectra and broadband wavelength coverage overlapping with the Ti:sapphire lasers wavelength range.

We demonstrate a 3 GHz, femtosecond Raman soliton source tunable from 1.15 µm to 1.35 µm. Using 30-cm photonic crystal fiber, the resulting Raman soliton pulse at 1.35 µm has 0.9 W average power. We also measure the relative intensity noise of the Raman soliton pulse at 1.35 µm and the integrated relative intensity noise is as low as 0.33% from 100 Hz to 10 MHz.

9198-6, Session 2

Application of four wave mixing in precise radio frequency dissemination *(Invited Paper)*

Xing Lu, Peking Univ. (China); Kebin Shi, Peking Univ. (China) and Collaborative Innovation Ctr. of Quantum Matter (China)

Highly stabilized radio frequency (RF) distribution techniques have played important roles for a variety of applications. It is one of the often used schemes to transfer RF via optical fiber based on optical frequency comb (OFC) generated in ultrafast mode-locked lasers, which provide the unique capability of bridging RF and optical carrier frequency. Phase comparison between local RF reference and reflected/circulated signal from remote is a commonly adapted approach for phase noise detection and cancellation in RF dissemination by propagating OFC in optical fiber. However, the unwanted reflection produced by interconnections along fiber link often results in detection artifacts. Previous work on OFC transferring regularly tackled this problem by choosing compromised launching power, fusion-splicing fiber interconnections and using separated backward fiber in the same bundle. In this paper, we report on a new phase noise detection scenario insusceptible to node reflection by combining OFC expansion generated by four wave mixing (FWM) in dispersion shifted fiber (DSF) and wavelength division multiplexing (WDM) technique. An experimental system based on a fiber link of 100km was demonstrated. The measured fractional stability was 1.5?10-13 at 1s and 1.7?10-16 at 1000s, indicating a white phase noise dominated process. Since only a narrow WDM bandwidth is used for propagating OFC modes, the new approach also exhibits less susceptibility to chromatic dispersion and seamless compatibility to commercial fiber network.

9198-7, Session 2

Mid-IR photothermal imaging with a compact ultrafast fiber probe laser *(Invited Paper)*

Hui Liu, Alket Mertiri, Atcha Totachawattana, Mi K. Hong, Tim Gardner, Shyamsunder Erramilli, Michelle Y. Sander, Boston Univ. (United States)

We demonstrate a mid-IR photothermal imaging system that incorporates an integrated erbium-doped ultrafast fiber laser at telecommunication wavelengths as a probe laser for the first time. A mid-IR pump laser is tuned to characteristic vibrational molecular modes. The scatter of the probe laser due to thermally induced changes in the refractive index of the sample is detected in a heterodyne lock-in measurement, yielding a highly sensitive, label-free microscopy method.

Previously, Helium-Neon lasers and Ti:sapphire lasers have been used as probe lasers in combination with a mid-IR quantum cascade pump laser for photothermal spectroscopy. Erbium-doped fiber lasers can operate in a wavelength regime between 1530nm to 1625nm, where there is very low absorption in the samples, which is critical to providing good measurement contrast. Thus, fiber lasers make an attractive probe laser source, as they feature a compact footprint, robust performance metrics and can utilize readily available commercial components at telecommunication wavelengths.

We custom-designed compact, all-fiber, high repetition rate probe lasers based on soliton mode-locking in anomalous gain fiber, butt-coupled to a semiconductor saturable absorber and connected to a 10%-output-coupler coated on a connector facet. Photothermal studies of a liquid crystal (4-Octyl-4'-Cyanobiphenyl (8CB)) sample were performed with the pump laser tuned to the CH-scissoring peak around 1607cm-1. Targeting the amide-I absorption band around 1650cm-1, images of biological samples of a song bird brain were recorded with good contrast. In summary, we demonstrated the versatility of a compact ultrafast probe laser for highly sensitive, mid-IR photothermal, label-free imaging.

9198-8, Session 3

Reactions of methanol molecules on TiO2 surfaces studied by in-situ surface sum frequency vibrational spectroscopy *(Invited Paper)*

Zefeng Ren, Anan Liu, Ranran Feng, Shuo Liu, Peking Univ. (China) and Collaborative Innovation Ctr. of Quantum Matter (China)

TiO2 material has attracted more and more attention in both scientific fields and industries due to its wide application in photosplitting of water and photodegradation of organic contaminants. Here, I will show our latest results of the reactions of methanol molecules on TiO2 film studied by in-situ surface sum frequency vibrational spectroscopy. We found both O2 and 266nm UV light can promote the dissociation of methanol to methoxy, and the substrate has huge non-resonant term under the UV irradiation. We preliminarily attribute the non-resonance to the excess electronic charge due to bridge-bonded hydroxyl groups on surfaces, which could play an important role in surface photocatalysis.

9198-9, Session 3

Probing metastable ferroelectric states exhibiting large property enhancements *(Invited Paper)*

Venkatraman Gopalan, The Pennsylvania State Univ. (United States)

Ferroelectrics are a well-known class of nonlinear optical materials such as BaTiO3, KNbO3, and LiNbO3. In this talk, I will discuss how the nonlinear optical coefficients in these materials can be increased by up to 4X by a slight distortion of the parent lattice which leads to new low symmetry phases. Nonlinear optical second harmonic generation microscopy, in combination with Nanoscale Xray diffraction imaging, Raman microscopy and piezoelectric force microscopy is used to probe these phases. Theoretical prediction of such enhancement in nonlinear SHG properties will be discussed. Variable Temperature SHG microscopy reveals the nature of the classic phase transitions in these materials to be thermotropic in nature.

9198-10, Session 3

Vibrational sum-frequency-generation (SFG) spectroscopy study of crystalline carbohydrate polymers: cellulose and starch *(Invited Paper)*

Seong H. Kim, The Pennsylvania State Univ. (United States)

Recently interests in cellulose have been growing significantly due to its potential as renewable recourse for conversion to transportation fuels or other value-added materials. Its availability for such applications greatly depends on the structure and their three-dimensional assembly of native cellulose crystallites or microfibrils in plant cell walls (industrially called biomass), which are not well understood yet to scientific communities. The currently accepted crystal structures of cellulose are constructed based on x-ray diffraction (XRD), nuclear magnetic resonance (NMR), and IR and Raman vibrational spectroscopy analyses of isolated and purified cellulose samples. Although these previous works greatly contributed to the structural understanding of crystalline cellulose, the existing models are not sufficient for full understanding of native cellulose and its roles in plant growth, physical properties, and recalcitrance to chemical and enzymatic degradation processes. This is in part due to the lack of proper characterization techniques that can relate structural information at all length scales: crystallographic unit cell at nanoscale, three dimensional assembly of cellulose microfibrils and their association with matrix wall polymers in cell walls at mesoscale, and phenotypes at macroscale. This talk will address how the noncentrosymmetry and phase matching conditions of the vibrational sum frequency generation (SFG) spectroscopy can be used to investigate the crystal structure and mesoscale assembly of cellulose microfibrils in biomass.

9198-11, Session 3

Structure of monolayer of organic molecules on water surface studied by phase sensitive sum frequency vibrational spectroscopy *(Invited Paper)*

Chuanshan Tian, Shumei Sun, Fudan Univ. (China)

In recent years, sum-frequency vibrational spectroscopy (SFVS) has been applied to studies of various water interfaces. It is the only technique that is capable of providing vibrational spectra of liquid water surface/interface. Generally speaking, structural information on a material can be deduced from its vibrational spectrum. In early studies, the SF vibrational spectra obtained for water/vapor interfaces were all intensity spectra, proportional to the absolute square of the surface nonlinear susceptibility, |X^(2)|^2 , which is an intrinsic response coefficient of the interface containing surface vibrational resonances. However, it only provides the amplitude of |X^(2)| , and the phase information is lost, while X^(2) is complex in general. To better characterize the resonances, one needs the spectrum of ImX^(2) , which is analogous to imaginary part of dielectric function for the absorption or emission spectrum. Recently, we have developed a phase-sensitive (PS) SFVS technique that produces ImX^(2) from experiment directly.

In this talk, I will present some of our recent progresses on technical development of PS-SFVS, as well as applications to the study of monolayer of organic molecules on water surface. To be more specific, we have studied the structure and ion adsorption at the interfaces of alkane/water, fatty acid/water, and long chain alcohol/water. The phase-sensitive sum-frequency vibrational spectroscopy produces ImX^(2) spectrum of the interface directly from experiment, which allows us to have better understanding of the water interfacial structure.

9198-12, Session 4

G-Fresnel spectrometer design and application

Chenji Zhang, The Pennsylvania State Univ. (United States); Perry Edwards, Atoptix, LLC (United States); Zhiwen Liu, The Pennsylvania State Univ. (United States)

Miniature optical spectrometers offer robust, portable platforms for spectroscopy, and often can perform with similar performance to their traditional, benchtop counterparts. However, despite an often significant reduction in price compared to the traditional technology, miniature high-performance spectrometers remain out of reach by the general consumer and are therefore mainly limited to applications in scientific or laboratory studies. Here, we present a high-performance cell phone spectrometer using the G-Fresnel - a hybrid diffractive optical element which combines dual dispersion and focusing capability in a single element. The G-Fresnel is combined with the built-in lens and camera in a cell phone creating a compact, portable spectrometer system that is simple yet maintains high-performance resolution capability. In this work, the system is shown to achieve high resolution over the entire visible spectrum.

9198-13, Session 4

Holographic collinear frequency resolved optical gating for spatio-temporal characterization of ultrafast optical pulse

Nikhil Mehta, Chuan Yang, The Pennsylvania State Univ. (United States); Yong Xu, Virginia Polytechnic Institute and State Univ. (United States); Zhiwen Liu, The Pennsylvania State Univ. (United States)

Ultrafast optical pulse characterization provides key insights in applications such as laser performance diagnostics, dynamic synthesis of ultrafast pulses for enhancing light-matter interactions, nonlinear microscopy optimization, coherent control of photons, etc. Furthermore, analysis of plasmonic systems featuring nanoscale modal distributions and large plasmonic resonance and of scattering media which exhibit non-trivial wavelength dependent speckle pattern under coherent pulsed illumination requires knowledge of the spatio-temporal evolution of the ultrafast pulse. However, commonly used characterization techniques often do not account for the coupled nature of spatial and temporal variation of the ultrafast pulse and assume that the “whole” beam may be represented using the characterized pulse width. Here we introduce a novel method, FROG holography, which records the spectral hologram of the collinear FROG trace. To illustrate our method, we perform numerical simulation to retrieve the complex profile and the relative phase of a simulated 37fs ultrafast optical pulse propagated over 15um through a fictitious medium and compute the group velocity. Further, we experimentally demonstrate our method using a stable reference field at the second harmonic frequency to retrieve the 75fs pulse at three axial locations in the vicinity of focus of an objective lens and also compute its group delay. Thus we show that FROG holography enables characterization of the spatio-temporal evolution of the ultrashort pulse.

9198-14, Session 4

Time and neighbor interaction in resonance Raman spectroscopy *(Invited Paper)*

Hans D. Hallen, Shupeng Niu, Ling Li, North Carolina State Univ. (United States)

We study systems in which the resonance Raman process is fast due to the requirement for phonon involvement in the absorption. The resonance enhancement is found to track the isolated atom, or vapor phase, absorption since the molecule does not have time to exchange energy with its neighbors. This corroborates with studies of pre-resonance, where Heisenberg’s uncertainty principle enforces a rapid process, but differs from resonance on electronically allowed transitions, where the resonance allows a relatively prolonged interaction. High resolution excitation spectroscopy reveals large gains and narrow features usually associated with the isolated atom. Vibration energies shift as the resonance is approached and the excited state vibration levels are probed. Several multiplets and overtone modes are enhanced along with the strongly coupled ring-breathing mode in aromatic molecules.

9198-15, Session 4

Miniature optofluidic darkfield microscope for biosensing *(Invited Paper)*

Zhenyu Li, The George Washington Univ. (United States)

Darkfield microscopy is an extremely sensitive imaging and sensing modality due to its low background. Metal nanoparticles as small as 20nm can been detected by darkfield imaging setups. However, traditional darkfield microscopes are bulky and require special illumination condensers, which limits their application in point-of-care biosensing. In this paper, we present a miniaturized darkfield microscope based on liquid metallic on-chip condensers and imaging lenses. This microscope is fully compatible with PDMS microfluidics and can be attached to a smartphone camera to build a complete handheld biosensing system with very high sensitivity and low cost.

9198-16, Session 4

Optical resonance spectroscopy with super-lattice nanostructure gratings *(Invited Paper)*

Junpeng Guo, Haisheng Leong, Hong Guo, The Univ. of Alabama in Huntsville (United States)

Optical resonance in resonant nanostructures has been measured traditionally with optical spectrometers in the transmission mode. Recently it was demonstrated that surface plasmon resonance in metal nanostructures can be measured in the diffraction mode by patterning nanostructures into a diffraction grating. The advantages of measuring optical resonance in the diffraction mode include integration of sensing and spectral measurement in a single system and eliminating the use of optical spectrometers, ultra-fast measurement of resonance spectrum with a single shot image capture, and increasing the signal-to-noise ratio of the resonant spectral measurement. In this talk, I will review recent experimental progress of this new spectroscopic technique and show that weak resonance modes in plasmon photonic super-lattice nanostructures can be measured by using this technique.

9198-17, Session 4

Single nanoparticle sensing using whispering-gallery microresonators and microlasers *(Invited Paper)*

Lan Yang, Washington Univ. in St. Louis (United States)

Optical sensors based on Whispering-Gallery-Mode (WGM) resonators have emerged as front-runners for label-free, ultra-sensitive detection of nanomaterials due to their superior capability to significantly enhance the interactions of light with the sensing targets by confining light photons in small volumes for long periods of time. I will introduce ultra-high-quality (Q) optical WGM microresonators and their fabrication process. The basis for resonator sensors is that the physical associations and interactions of nanomaterials on the surface of a high-Q optical WGM resonator alter the trajectory and lifetime of photons in a way that can be measured and quantified. I will present a process to create active devices based on a sol-gel oxide delivery process, which enables spin-coating of high quality oxide films to achieve ultra-high-Q resonators on silicon wafers. It is also a convenient and efficient method to incorporate optical gain dopants into the oxide layer deposited on a silicon wafer, providing a route to achieve arrays of microlasers on silicon wafer with emission spectral windows from visible to infrared. I will then present a recent discovery of using ultra-high-Q microresonators and microlasers for ultra-sensitive self-referencing detection and sizing of single virion, dielectric and metallic nanoparticles. Finally, I will discuss using optical gains in a microlaser to improve the detection limit beyond the reach of a passive microresonator. These recent advancements in WGM microresonators will enable a new class of ultra-sensitive and low-power sensors for investigating the properties and kinetic behaviors of nanomaterials, nanostructures, and nanoscale phenomena.

9198-18, Session 5

Excitonic dynamics in two-dimensional transition metal dichalcogenides *(Invited Paper)*

Hui Zhao, The Univ. of Kansas (United States)

Recently, there is a growing interest in exploring new types of novel two-dimensional crystals that composed of a single layer of atoms,

such as transition metal dichalcogenides. Recent studies have revealed several interesting properties in these systems, including an indirect-to-direct bandgap transition, larger nonlinear response, and valley and spin selective optical coupling. Based on their novel optical and transport properties, applications of these two-dimensional crystals in transistor, photovoltaic, photo-detector, and light-emitting diodes have been proposed and studied.

Due to their extremely small thickness, the exciton binding energies in these two-dimensional crystals are unusually large. Hence, excitons play dominant roles in optical processes in these materials.

Here we discuss our recent investigations on excitonic dynamics in two-dimensional transient metal dichalcogenides, such as MoS2, MoSe2, WS2, and WSe2, by using high-resolution transient absorption microscopy. Spatially and time resolved transient absorption measurements allow us to determine several fundamental parameters describing the exciton dynamics, such as recombination lifetime, diffusion coefficient, diffusion length, mean free time, and exciton mobility. Samples with different thickness and are compared. Furthermore, polarization and time resolved transient absorption measurements allow us to observed spin and valley selective optical excitation and detection of excitons, and determine the spin and valley-polarization relaxation time in these two-dimensional crystals.

9198-19, Session 5

Ultrafast valley relaxation dynamics in single layer semiconductors *(Invited Paper)*

Kenan Gundogdu, Linyou Cao, Cong Mai, Andrew Barrette, Yifei Yu, Ki Wook Kim, Yuriy G. Semenov, North Carolina State Univ. (United States)

Single layer transition metal dichalcogenides are 2D semiconducting systems with unique electronic band structure. Two-valley energy bands along with strong spin-orbital coupling lead to valley dependent career spin polarization, which is the basis for recently proposed valleytronic applications. These systems also exhibit unusually strong many body affects, such as strong exciton and trion binding, due to reduced dielectric screening of Coulomb interactions. Recently observed large photoluminescence helicity suggests beyond ns hole spin and valley lifetimes. But there is not much known about the impact of strong many particle correlations on spin and valley polarization dynamics. Here we report direct measurements of ultrafast valley specific relaxation dynamics in single layer MoS2 and WS2. We found that excitonic many body interactions significantly contribute to the relaxation process.. Biexciton formation reveals hole valley/spin relaxation time. Our results suggest that initial fast intervalley electron scattering and electron spin relaxation leads to loss of valley polarization for holes through an electron-hole exchange mechanism.

9198-20, Session 5

Second harmonic generation in tungsten disulfide monolayers

Corey Janisch, Yuanxi Wang, Ding Ma, Nikhil Mehta, Ana Laura-Elias, Nestor Perea-Lopez, Mauricio Terrones, Vincent Crespi, Zhiwen Liu, The Pennsylvania State Univ. (United States)

Two-Dimensional (2D) layered materials have garnered interest due to their exciting optical and electronic properties. The transition metal dichalcogenide (TMD) family of monolayer materials (such as MoS2, WS2) has demonstrated extraordinarily high photoluminescence and nonlinear optical generation. In this work, we investigate Second Harmonic Generation (SHG) in Tungsten Disulfide (WS2) monolayers both grown on Si/SiO2 substrates and suspended on a transmission electron microscopy grid; we find an unusually large second order susceptibility of deff ~ 4.5 nm/V, which is nearly three orders of magnitude larger than common nonlinear crystals. In order to characterize the nonlinear susceptibility, we developed a formalism to model the SHG from a 2D layer using a focused plane wave and the effects of the substrate. To further understand this enormous nonlinearity in 2D WS2, we performed density functional theory based calculations that reveal a second order nonlinear susceptibility value of deff ~ 0.61 nm/V, providing good order-of-magnitude agreement with our experimental data. Due to this extraordinarily high nonlinear susceptibility in a sub-nanometer thick crystal, TMD monolayers could have potential for exciting novel layered nonlinear optical devices.

9198-21, Session 5

Helicity Resolved Ultrafast Pump-Probe Spectroscopy of Monolayer Molybdenum Disulphide *(Invited Paper)*

Qinsheng Wang, Dong Sun, Peking Univ. (China)

We investigate the valley related carrier dynamics in monolayer MoS2 using helicity resolved non-degenerate ultrafast pump-probe spectroscopy at the vicinity of the high-symmetry K point under the temperature down to 78 K. Under the pump photon energy 1.964 eV and probe photon energy 1.912 eV, both bilayer and bulk show positive dR during the entire course of the measurements, while the initial transient reflection spectra of monolayer are different with different helicity pump excitations. The difference is observable over period of several ps. We suggest that the dynamical degradation of valley polarization is attributable primarily to the exciton trapping by defect states.

If the pump photon energy increases slightly to 2.072eV, the pump helicity dependence completely disappears, it means initial valley carrier polarization by the excitation is not observed within the ~200 fs time resolution. Thus, the absence of the valley polarized CD is not attributable to the phonon assisted intervalley scattering, as carrier phonon scattering timescale is larger than 200-fs. The only interpretation would be that the valley CD selectivity decays quickly when the excitation is away from the vicinity of the high symmetry K point, and thus 2.072eV pump excites carriers almost equally in K and K? valleys initially. A tight-binding model analysis also show that the perfect valley circular dichroism(CD) selectivity is fairly robust against disorder at the K point, but quickly decays from the high-symmetry point in the momentum space in the presence of disorder.

9198-22, Session 6

Imaging of molecules in the gas phase with ultrafast electron diffraction *(Invited Paper)*

Jie Yang, Omid Zandi, Ping Zhang, Martin Centurion, Univ. of Nebraska-Lincoln (United States)

We present results on imaging of molecules using femtosecond electron pulses. We have previously shown that a 3D image of a symmetric-top molecule can be retrieved from diffraction patterns of aligned molecules. The molecules were aligned impulsively with a femtosecond laser pulse, and probed by an electron pulse in a field-free environment (after the laser pulse has traversed the sample). Further improvements on our phase retrieval method have allowed us to extend the technique also to asymmetric molecules. We have recently applied this method to investigate the effect of a strong alignment laser pulse on the structure and rotational dynamics of linear molecules, with the goal of obtaining the highest possible alignment without disturbing the molecular structure. A key advantage of electron diffraction is that both the angular distribution and the structure can be retrieved from the diffraction patterns. We will also report on our progress in building a new setup that includes and RF cavity to compress the electron pulses. This new setup will deliver shorter electron pulses and much higher beam current, resulting in improved temporal and spatial resolution.

9198-23, Session 6

Femtosecond photoelectron diffraction: a new approach to image molecular structure during photochemical reactions *(Invited Paper)*

Daniel Rolles, Max-Planck-Arbeitsgruppen für strukturelle Molekularbiologie (Germany); Rebecca Boll, Denis Anielski, Deutsches Elektronen-Synchrotron (Germany) and Max-Planck-Institut für Kernphysik (Germany); Cédric Bomme, Deutsches Elektronen-Synchrotron (Germany); Evgeny Savelyev, Deutsches Elektronen-Synchrotron (Germany) and Georg-August-Univ. Göttingen (Germany); Artem Rudenko, Kansas State Univ. (United States)

Continuing technical advanced in the creation of (sub-) femtosecond X-ray pulses with X-ray Free-Electron Lasers (XFELs) and laser-based high harmonic generation (HHG) sources have created new opportunities for studying ultrafast dynamics during chemical reactions. Here, we present an approach to image the geometric and electronic structure of gas-phase molecules with few-femtosecond temporal and few Ångström spatial resolution using femtosecond photoelectron diffraction [1,2,3]. This technique allows imaging the molecules “from within” by analysing the diffraction of inner-shell photoelectrons that are created by femtosecond VUV and X-ray pulses e.g. from Free-Electron Lasers. Using pump-probe schemes, ultrafast structural changes, e.g. during photochemical reactions can thus be directly visualized.

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[2] R. Boll et al., Femtosecond Photoelectron Diffraction on Laser-Aligned Molecules: Towards Time-Resolved Imaging of Molecular Structure, Phys. Rev. A 88, 061402(R) (2013).

[3] D. Rolles et al., Femtosecond X-Ray Photoelectron Diffraction on Gas-Phase Dibromobenzene Molecules, submitted to J. Phys. B (2013)

9198-24, Session 6

Femtosecond low-energy electron diffraction and imaging *(Invited Paper)*

Melanie Müller, Alexander Paarmann, Ralph Ernstorfer, Fritz-Haber-Institut der Max-Planck-Gesellschaft (Germany)

The recent development of femtosecond electron and x-ray diffraction and imaging techniques allows for the direct observation of structural dynamics in the course of photo-induced chemical or physical processes with atomic spatial and femtosecond temporal resolution. We aim at investigating ultrafast structural dynamics in low-dimensional systems like two-dimensional materials, surfaces, and nanostructures, which asks for a time-resolved diffraction technique with maximal scattering cross section as provided by low-energy electrons in the sub-kV range. We developed a novel setup for femtosecond low-energy electron diffraction (fs-LEED) and point projection imaging (fs-PPI) in the energy range from 50 to 1000 eV based on a laser-triggered metal nanotip. Femtosecond time resolution is achieved by using a compact geometry with sub-mm propagation distances, which minimizes dispersive temporal broadening of the electron wave packets [1].

The instrument provides two operation modes: i) fs-PPI utilizes the high sensitivity of low-energy electrons to weak electric fields, which allows for mapping of transient electric fields and ultrafast currents in photoexcited nanostructures. Specifically, we investigate carrier transport upon above-bandgap excitation in axially doped InP nanowires. ii) fs-LEED requires a collimated electron beam. In order to maintain the short propagation distances in fs-LEED experiments, we developed a compact microlens coated directly onto the shaft of the nanotip to collimate the intrinsically divergent electron beam without any optics between tip and sample [2]. We present first experimental data on transmission LEED of free-standing monolayer graphene.

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[2] S. Lüneburg et al., Appl. Phys. Lett 103, 213506 (2013).

9198-25, Session 6

The perspectives of femtosecond imaging and spectroscopy of complex materials using electrons *(Invited Paper)*

Chong-Yu Ruan, Phiilp M Duxbury, Martin Berz, Michigan State Univ. (United States)

The coexistence of various electronic and structural phases that are close in free-energy is a hallmark in strongly correlated electron systems with emergent properties, such as metal-insulator transition, colossal magnetoresistance, and high-temperature superconductivity. The cooperative phase transitions from one functional state to another can involve entanglements between the electronically and structurally ordered states, hence deciphering the fundamental mechanisms is generally difficult and remains very active in condensed matter physics and functional materials research. We will outline the recent experimental and theoretical studies of metal-insulator transitions in vanadium dioxide and 2D charge-density wave materials, including the nonequilibrium electron dynamics unveiled by ultrafast optical spectroscopy-based techniques sensitive to the electronic order parameter. We will also describe the most recent findings from ultrafast electron crystallography, which provide crucial structural aspects to correlate lattice dynamics with electronic evolutions to address the two sides of a coin in the ultrafast switching of a cooperative state. These new results shed light on several controversial issues and bring forth new perspectives in understanding light-matter interactions and various switching mechanisms in strongly correlated systems with many potential applications. Finally, we will discuss the prospects of implementing new ultrafast electron imaging as a local probe incorporated with femtosecond select-area diffraction, and spectroscopy to provide the full scope of resolution to tackle the more challenging complex phase transitions on the femtosecond-nanometer scale.

9198-26, Session 6

Ultrabright femtosecond electron sources: perspectives and challenges towards the study of structural dynamics in labile systems *(Invited Paper)*

Germán Sciaini, Univ. of Waterloo (Canada); Meng Gao, Hubert Jean-Ruel, Cheng Lu, Lai C. Liu, Univ. of Toronto (Canada); Alexander Marx, Max-Planck-Institut für Struktur und Dynamik der Materie (Germany); Ryan R. Cooney, Univ. of Toronto (Canada); Yifeng Jiang, Gunther Kassier, Max-Planck-Institut für Struktur und Dynamik der Materie (Germany); Gustavo Moriena, Univ. of Toronto (Canada); R. J. Dwayne Miller, Max-Planck-Institut für Struktur und Dynamik der Materie (Germany)

The advance on femtosecond electron sources over the last thirty years has been remarkable. In particular, the development of ultrabright femtosecond electron sources has made it possible the observation of molecular motions in labile organic materials and it is paving the way towards the study of complex protein systems. The principle of radio frequency (RF) rebunching cavities for the compression of ultrabright electron pulses is presented, alongside with a recent demonstration of its capabilities in capturing the relevant photoinduced dynamics in weakly scattering organic systems. Organic and biological systems can easily decompose or lose crystallinity as a consequence of cumulative heating effects or the formation of side reaction photo-products. Hence, source brightness plays a crucial role in achieving sufficient signal-to-noise

ratio before degradation effects become noticeable on the structural properties of the material. The current brightness of electron sources in addition to the high scattering cross section of keV-MeV electrons have made femtosecond electron diffraction a powerful tool for the study of materials composed by low-Z atomic elements[1].

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9198-27, Session 6

MeV ultrafast electron microscopy *(Invited Paper)*

Pietro Musumeci, Renkai Li, Univ. of California, Los Angeles (United States)

An active research area to further enhance the capability of state-of-the-art transmission electron microscopies is to dramatically improve their temporal resolving power, which will enable us to visualize in real time many ultrafast dynamic processes in biology, chemistry, and material science. Progress in this direction critically depends on the generation, precise control and advanced diagnosis of electron beams with unprecedented brightness, including ultrasmall emittance, ultralow energy spread, and high beam current. Here we present the feasibility study of a single-shot ultrafast transmission electron microscopy using high brightness electron beams from a high gradient photocathode radiofrequency electron gun aiming at a few picoseconds temporal resolution and a few tens of nanometers spatial resolution. We will discuss several key technical innovations optimized to address the challenging demand on beam quality, including the generation of pico-Coulomb charge ultralow emittance beam in the cigar-aspect-ratio regime, the RF curvature regulation technique to greatly reduce the beam energy spread, and strong electron optics using permanent quadrupole magnets or nano-fabricated micro-quadrupoles. Effects of collective space charge forces and stochastic Coulomb scattering on the achievable spatial resolution will also be discussed.

9198-28, Session 7

Fiber continuum and phase shaping for multicolor two-photon excited microscopy *(Invited Paper)*

Ling Fu, Britton Chance Ctr. for Biomedical Photonics (China); Quan Cui, Wuhan National Lab. for Optoelectronics (China)

Two-photon excited fluorescence (TPEF) is widely used for thick or live samples due to its deep penetration, inherent sectioning ability and decreased photobleaching. However, in order to efficiently excite multiple fluorophores for TPEF, the spectral band of standard 100-fs Ti: Sapphire oscillators is not sufficient because the optimal excitation wavelengths of multiple fluorophores are different. By pumping pulses from the 100-fs Ti:Sapphire oscillator through the highly nonlinear photonic crystal fibers (HNPCF), we demonstrated that linear compressible continuum covering most of fluorephores can be generated due to enhanced self-phase modulation. With phase shaping, such a continuum can be compressed to 10fs at the objective focus which greatly enhance the signal level of multicolor TPEF microscopy. We also demonstrate that with fiber continuum rapid selective excitation of specified fluorophores can efficiently decrease the spectral crosstalk between multiple fluorophores. This work shows its potential to promote multicolor two-photon fluorescence microscopy in the application for in vivo imaging by using fiber continuum and phase shaping.

9198-29, Session 7

Time- and polarization-resolved cellular autofluorescence for quantitative biochemistry on living cells *(Invited Paper)*

Ahmed A. Heikal, Univ. of Minnesota, Duluth (United States)

Nicotinamide adenine dinucleotide (NADH) and flavin adenine dinucleotide (FAD) are enzyme cofactors that participate in oxidation-reduction reactions in energy metabolism and a myriad of other biochemical reactions in living cells and tissues. These coenzymes are naturally fluorescent and their redox partners (NAD+ and FADH2) are not. Therefore, these cofactors have the potential to serve as endogenous biomarkers for mitochondrial activity, apoptosis, oxidative stress, aging, and neurodegenerative diseases. In this contribution, we employ two-photon fluorescence lifetime imaging microscopy (FLIM) and time-resolved anisotropy imaging of intracellular NADH and flavins for quantitative, non-invasive biochemistry on living cells and tissues. In contrast with steady-state one-photon, UV-excited autofluorescence, two-photon FLIM is sensitive to both molecular conformation and stimuli-induced changes in the local intracellular environment with minimal photodamage and inherently enhanced spatial resolution. Time-resolved, two-photon anisotropy imaging of cellular and brain-tissue autofluorescence allows us to quantitatively assess the binding state and environmental restrictions of the tumbling motion of these coenzymes. These measurements reveal that both free and enzyme-bound NADH exist at equilibrium, where the enzyme-bound fraction is dependent on the physio-pathological state of the cell. In contrast, most of cellular flavins are protein-bound. Parallel studies on NADH-enzyme binding in bulk solution serve as a point of reference for analyzing autofluorescence in living cells and tissues. These autofluorescence-based approaches complement conventional analytical biochemistry methods that require the destruction of cells and tissues and, importantly, serve as a critical step towards using NADH and flavins for in vivo biomedical diagnostics.

9198-30, Session 7

Pushing the limits of nonlinear microscopy *(Invited Paper)*

Chris Xu, Cornell Univ. (United States)

Multiphoton microscopy has been applied to imaging deep in scattering tissue because of its intrinsic 3D localized excitation. However, the imaging depth of conventional MPM was still limited to less than 1 mm. In this talk, the fundamental challenges of deep tissue, high-resolution optical imaging are discussed. New technologies for deep and fast in vivo multiphoton imaging in intact mouse brain will be presented.

9198-31, Session 7

Two-photon three-axis digital scanned light-sheet microscopy (2P3A-DSLM) *(Invited Paper)*

Liangyi Chen, Peking Univ. (China)

In this presentation we report a new 3D scanned DSLM. The system combined 1) two-photon excitation, 2) scanning along the illumination axis (x-axis) using tunable acoustic gradient lens (TAG) to stretch the Rayleigh range [5], 3) scanning vertically to the illumination axis (y-axis) by one galvo mirror to create light sheet. 4) scanning along Z-axis to do fast 3D imaging by another galvo mirror. The image plane was kept aligned with the fast z-axis scanned light sheet plane by an electric tunable lens (ETL) as described in ref. 6. The light sheet can be tailored to any shape between 50?50 ?m2 and more than 500?500 ?m2 with constant thickness limited by diffraction and fast imaging rates limited by the detector. The tailorable illumination area allows multi-scale field of view (FOV), and is consequently capable of imaging cells, tissue and live animals in one setup.

9198-32, Session 8

Photocyclization dynamics revealed by ultrafast spectroscopy

Mohammadhassan Valadan, Univ. degli Studi di Napoli Federico II (Italy); Marco Micciarelli, Univ. degli Studi di Roma La Sapienza (Italy); Bartolomeo Della Ventura, Felice Gesuele, Carlo Altucci, Raffaele Velotta, Univ. degli Studi di Napoli Federico II (Italy)

Interactions between DNA and Proteins generally are fundamental in biological sciences. Irradiation with a high intensity UV laser greatly increases the efficiency of protein-nucleic acid cross-linking. It's however difficult to investigate this in the presence of very complex molecules. Therefore photocyclization process in 5-Benzyluracil (5BU) to produce 5,6-Benzyluracil (5,6-BU) has been proposed as a model system of crosslink reactions; in which the absorbed UV photons induce proton transfer and a new covalent bond form.

We're setting up a pump-probe apparatus where ultrashort UV laser pulse is split into two replicas: One is used to trigger the photocyclization process, whereas the second is properly delayed to probe 5,6-BU formation. Considering that a very small portion of the 5BU molecules photocyclize with the first pulse, and a small portion of them will be excited by the second pulse to decay with fluorescence radiation, we'll discriminate the two contributions not only from the spectrum, but also by time-gating the light acquisition so that the short lifetime fluorescence coming from 5BU will be essentially cut while 5,6-BU is still emitting. We estimate that the fluorescence signal from 5BU will be about 5 orders of magnitude stronger than the signal of 5,6-BU fluorescence. Another knob we can exploit is the difference in the anisotropy of fluorescence of 5- and 5,6-benzyluracil; While 5BU fluorescence is strongly polarized, no significant polarization is expected from 5,6-BU fluorescence. Thus, the collection of the fluorescence in a crossed polarizers configuration will improve the signal to noise ratio even more.

9198-33, Session 8

Optical two-dimensional coherent spectroscopy of semiconductor nanostructures *(Invited Paper)*

Gael Nardin, Travis Autry, JILA (United States); Galan Moody, JILA / NIST & University of Colorado (United States); Rohan Singh, JILA (United States); Hebin Li, JILA / NIST & University of Colorado (United States); Steven Cundiff, JILA (United States)

Optical two-dimensional coherent (2DC) spectroscopy is a powerful method for studying semiconductor nanostructures such as quantum wells and quantum dots. For studying quantum wells, the ability of 2DC spectroscopy to reveal coupling between resonances, along with information about the microscopic mechanism, is particularly useful. For example, a combination of different types of 2DC spectra reveal that many-body interactions are responsible for the coupling between InAs quantum wells. In a doped quantum well, 2DC shows that excitons and trions are coherently coupled, which is surprising because they are expected to be spatially separated. When used to study quantum dot ensembles, the ability of 2DC spectroscopy to make measurements as a function of energy within an inhomogeneously broadened distribution means that size resolved measurements can be made. This ability is used to measure the biexciton binding energy and phonon-induced broadening as a function of quantum dot size. The results can differ from single-dot studies, which suggest that the sample preparation needed for single dot studies may introduce additional extrinsic effects.

9198-34, Session 8

Ultrafast spectroscopy toward generating coherence in a few quantum materials *(Invited Paper)*

Jimin Zhao, Institute of Physics (China)

Being a natural phase-sensitive experimental means, ultrafast spectroscopy has been used to generate coherence in all the degrees of freedom in various condensed maters, which offers a unique means to control the quantum states therein. Here I present our ultrafast spectroscopy investigation of a few quantum materials, including graphene, MoS_2, and iron based superconductors. Using ultrafast laser pulses we are able to generate and correlate the electronic coherence in and between flaky domains of electronic systems, through a nonlinear optical process of spatial self-phase modulation. Also we generated and detected coherent (optical and acoustic) phonons in iron based superconductors $FeSe_{0.5}Te_{0.5}$ and metallic FeTe thin films, respectively. From the initial phase we obtain clues to the electron-phonon interaction that is related to the superconducting phase transition.

9198-35, Session 9

Restoration of blurred images based on phase conjugation by using single second-order nonlinear parametric processes *(Invited Paper)*

Yujie J. Ding, Lehigh Univ. (United States)

During this presentation, we will summary our recent progress made by my group on correction of blurred images caused by atmospheric turbulence by using phase-conjugated beams generated by difference-frequency generation in stacked KTP plates. We have demonstrated that when the incoming beam is phase-distorted the phase-conjugated beam can be used to clean up the distortion. We have further demonstrated that image quality can be completely restored after the phase distortion. This represents a novel approach for image restoration based on nonlinear optics. The image correction is insensitive to the polarization of the incoming beam. Our approach is instantaneous. Furthermore, the pump power as low as 1 mW is required to reach the nonlinear power reflection coefficient of 100%. Therefore, it is ideal for us to correct the blurred images caused by atmospheric turbulence using our approach.

9198-36, Session 9

Adaptive control of waveguide modes in a mulitmode waveguide *(Invited Paper)*

Peng Lu, Matthew Shipton, Virginia Polytechnic Institute and State Univ. (United States); Yong Xu, Virginia Tech Ctr. for Photonics Technology (United States)

We experimentally realize an adaptive optics (AO) technique capable of achieving highly selective excitation of linearly polarized (LP) modes in a two-mode fiber (TMF). We use a phase-only spatial light modulator (SLM) to control the wavefront of an incident beam, using feedback signals provided by the correlation between the experimentally measured field distribution and the desired LP mode profiles. Experimental results show the optical field within the TMF can be shaped to be a pure LP mode or a combination of different LP modes. Analysis shows selective mode excitation can be achieved using only 5?5 independent phase blocks. With proper feedback signals, this method should enable one to precisely control the optical field within any multimode fibers or waveguides in real time. The AO based technique may also be used to control the propagation of ultrafast optical signals within multimode fibers or waveguides.

9198-37, Session 9

Imaging with multi-mode fibers *(Invited Paper)*

Demetri Psaltis, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We will describe how multi-mode fibers can be used to build endoscopes and form high quality images. The attractive feature of multi-mode fiber endoscopes is their small diameter, a consequence of the fact that there are no active scanning devices at the far (distal) end. The scanning is done electronically through a spatial light modulator that controls the wavefront of the illuminating beam at the near (proximal) end of the endoscope.

9198-38, Session 9

Imaging of terahertz fields and responses *(Invited Paper)*

Keith A. Nelson, Massachusetts Institute of Technology (United States)

In recent years it has become possible to generate terahertz-frequency (THz) fields that are strong enough to induce nonlinear responses in ordinary molecules and materials. Part of the development of THz technology and nonlinear spectroscopy has relied on optical imaging of THz field profiles and their time and position-dependent evolution. A THz “polaritonics” platform enables extensive control over THz fields that are generated; integration of functional elements such as bandgap structures and metamaterial devices; optical imaging of the THz near and far fields with subcycle temporal and subwavelength spatial resolution; and exploitation of the results for nonlinear spectroscopy.

9198-39, Session 9

Metal-free flat lens using negative refraction by nonlinear four-wave mixing *(Invited Paper)*

Jianjun Cao, Yuanlin Zheng, Yaming Feng, Xianfeng Chen, Shanghai Jiao Tong Univ. (China); Wenjie Wan, Shanghai Jiao Tong Univ. (China) and Univ. of Michigan-Shanghai Jiao Tong Univ. Joint Institute (China)

A flat lens utilizing negative refraction contrasts sharply with traditional lenses for its unique ability to focus light at the nanoscale. In linear optics, such negative refraction can only occur in materials with designed spatial dispersion such as metals, meta-materials and photonics crystals, all of them are difficult to fabricate, suffer high loss and work only in microscale if for imaging applications. In nonlinear optics, alternative approaches to achieve negative refraction are proposed using third order nonlinearity, e.g. phase conjugation and four-wave mixing. However, up to now, few experiments have realized imaging functionality at the macro-scale. Here we demonstrate a new type of flat lens by negative refraction using the degenerate four wave mixing (4WM) process. We realize direct nonlinear image (of different color) of the original target behind a thin lens with a strong pump beam at frequency ?1 and a probe beam at frequency ?2 which carrying the original image. A signal beam at frequency 2*?1-?2 is negatively refracted with respect to the input probe beam and form the final image. By using this effect, we further realize imaging in non-collinear and collinear configuration. Clear images formed by the 4WM wave are observed. Our methods show that a planar nonlinear medium can act as a flat lens, which is desired in imaging systems and may find further applications in super resolution imaging.

9198-40, Session PMon

Label-free imaging of biological sample with multimodal multiphoton nonlinear microendoscopy

Jang Hyuk Lee, Myoung-Kyu Oh, Do-Kyeong Ko, Gwangju Institute of Science and Technology (Korea, Republic of)

Multimodal multiphoton nonlinear microscopic imaging systems have powerful advantages of label-free imaging, deep penetration, high sensitivity, and chemical specificity. However, due to the large size of objective lenses required in these instruments, their applications have been mostly limited to superficial tissues such as the skin or to surgically exposed internal organs. Hence, in vivo imaging techniques are needed to accelerate the biomedical tissue study. To overcome the limitation, multimodal multiphoton nonlinear optical microendoscopy imaging system based on a small diameter probe has been developed, providing access to tissues in intact organs. Objective lens (10x, 0.25 NA) is used to inject light into gradient-index (GRIN) lens (4.8x, 0.8 NA) in the microendoscope. The system allows for simultaneous Coherent anti-Stokes Raman scattering (CARS) microendoscopy imaging and two-photon excitation fluorescence (TPEF) microendoscopy imaging, and it was applied to biological tissue samples such as liver fibrosis and brain tissue. The field of view (FOV) of a microendoscope is typically proportional to the diameter of the GRIN lens and is relatively small compared to a standard objective lens. Despite its small diameter we used, the multimodal nonlinear microendoscope has high speed over wide areas of tissue at sufficient resolution to quantify subtle differences in bio-molecules. We expect the system as a great early diagnosis tool for diseases such as liver or neurological disorder at tissue level.

9198-42, Session PMon

Generation of an octave-spanning supercontinuum in highly nonlinear fibers pumped by noise-like pulses

Shih-Shian Lin, National Chiao Tung Univ. (Taiwan); Sheng-Kwang Hwang, National Cheng Kung Univ. (Taiwan); Jia-Ming Liu, National Chiao Tung Univ. (Taiwan) and Univ. of California, Los Angeles (United States)

A supercontinuum generation system is developed, which consists of an erbium-doped fiber ring laser, an erbium-doped fiber amplifier, and a 100-m highly nonlinear fiber. The fiber ring laser is so operated that a train of noise-like pulses is generated through nonlinear polarization rotation. Before sending the noise-like pulses into the highly nonlinear fiber, their energy is amplified up to 13 nJ by the fiber amplifier. As a result, an octave-spanning supercontinuum from 1177 nm to 2449 nm is obtained, where a 20-dB spectral width of 980 nm is achieved. Because of the nonlinearity of the fiber amplifier, the duration of the noise-like pulses is shortened while their average power is enhanced. However, the enhanced pulse energy makes the key contribution to the spectral broadening of the resulting spuercontinuum in this study since the highly nonlinear fiber is so long that the effect of the pulse compression on supercontinuum generation becomes weak.

9198-43, Session PMon

Raman spectroscopy for monitoring of organic and mineral structure of bone grafts

Elena V. Timchenko, Pavel E. Timchenko, Samara State Aerospace Univ. (Russian Federation); Larisa T. Volova, Julia V. Ponomareva, Samara State Medical Univ. (Russian Federation); Larisa A. Taskina, Svetlana V. Pershutkina, Samara State Aerospace Univ. (Russian Federation)

The fabrication process of quality bone grafts has several important requirements and criterions. Thus, grafts with various degree of demineralization are required for the regulation of regenerative processes in the patient's bone tissues. The control of demineralization degree is carried out using biochemical methods that takes a long time. Eventually, it influence on time and outcome of providing health care to patients.

Raman spectroscopy is one of perspective methods for the structural features study of organomineral objects such as bone. The method allows to obtain information with a high spatial resolution (up to 1 mkm), with easy sample preparation and absence of damage after analyzing. Also, the method provides an estimate of the mineral relationships in sample composition.

The purpose of study is a diagnostics of bone grafts by Raman spectroscopy. The allogeneic bone native biomaterial and allogeneic bone biomaterial with the varying degrees of demineralization were used as research objects. The results were compared with standard biochemical analysis of bone objects. Raman spectroscopy has been implemented by a high-resolution digital spectrometer Shamrock sr-303i (focal length of 303 mm) with ANDOR DV-420A-OE integrated digital camera (1024*256). 785 nm laser source was used for excitation of Raman spectrum. The characteristics of Raman spectra for native bone grafts and grafts with varying demineralization degrees (the Raman shift, the ratio of carbonate/phosphate and mineral/organic matrix) were processed by «Wolfram Mathematica»'8 tool. The distribution of organic substances was assessed by stretching vibrations ?s (PO), ?s (CO) and amide I.

The research results are the following: Raman spectra features of native and demineralized bone were identified; the relative content of phosphate was depended on the demineralization extent of bone tissue; dependence of bone mineral / organic matrix from demineralization degree was obtained.

9198-44, Session PMon

Computational imaging based on the Hanbury Brown and Twiss effect

Yizhu Chen, Zhiwen Liu, The Pennsylvania State Univ. (United States)

In this paper, we will discuss a novel computational imaging method based on the Hanbury Brown and Twiss effect. The proposed imaging system is lensless, resulting in a simple design and cost-effectiveness. It has a large depth of focus, and can allow for imaging of 3D objects over a wide field of view. Preliminary numerical simulation results will be presented.

9198-45, Session PMon

High-speed and two-photon in-vivo imaging of neutrophil in ear skin of mice

Bo Ram Kim, Eung Jang Lee, Seung-Han Park, Yonsei Univ. (Korea, Republic of)

Neutrophils are attributed to be one of the most important players during inflammation. However, it has been difficult to get clear visualization of dynamic behaviors of rapidly flowing neutrophils in the blood vessel and their transmigration inside scattering tissue due to the lack of spatio-temporal resolution of the imaging system.

In this presentation, two-photon in-vivo imaging of neutrophil trafficking across the venule in ear skin of mice will be demonstrated. In order to get in-vivo images, we have constructed high-speed two-photon microscopy. Our system, based on an upright wide-field fluorescent microscope, is equipped with resonant scanner (8 kHz) and galvanometric mirror scanner for fast and slow axes, respectively. By utilizing this system, we can achieve 30 frames per second in 791?512 pixels image. BALB/c mice aged six weeks were employed for the in-vivo experiment. To visualize the neutrophil and endothelia cell, they were labeled by intravenous injection of anti-Ly-6G (Gr-1) antibody conjugated with eFluor® 450 and anti-CD31(PECAM-1) antibody conjugated with APC into the lateral tail vein.

Conference 9199:
Terahertz Emitters, Receivers, and Applications V

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9199-1, Session 1

RT,CW operation of 3.5 THz laser diode based on DFG-QCL *(Invited Paper)*

Manijeh Razeghi, Quan-Yong Lu, Neelanjan Bandyopadhyay, Steven Slivken, Yanbo Bai, David Heydari, Wei Zhou, Northwestern Univ. (United States)

Terahertz (THz) (? ~0.5-10 THz, ? ~30–600µm) frequencies are among the least explored of the electromagnetic spectrum mainly due to the lack of suitable sources of coherent radiation. A compact, high power, room temperature, continuous wave terahertz semiconductor source will greatly benefit terahertz system development for applications in terahertz spectroscopy, communication, sensing, and imaging. Here we demonstrate the first room temperature continuous wave THz sources based on intracavity difference frequency generation in mid-infrared quantum cascade lasers. A buried ridge, buried dual-period grating waveguide with ?erenkov phase matching scheme is used for low threshold operation and high efficient THz generation. Room temperature single mode emissions in 3.5-3.8 THz with continuous wave emitting power of 3 mW with mid-IR-to-THz conversion efficiency of 0.5 mW/W2 are obtained. THz peak power up to 1.4 mW in pulsed mode operation with mid-IR-to-THz conversion efficiency of 1 mW/W2 at 3.5 THz is also demonstrated.

9199-2, Session 1

Processing of AlGaAs/GaAs QC structures for terahertz laser *(Invited Paper)*

Anna Szerling, Institute of Electron Technology (Poland); Kamil Kosiel, Michal O. Szymanski, Institute of Electron Technology (Poland); Zbigniew R. Wasilewski, Univ. of Waterloo (Canada); Artur Trajnerowicz, Krystyna Golaszewska, Maciej Sakowicz, Adam Laszcz, Mariusz Pluska, Institute of Electron Technology (Poland); Michal Walczakowski, Norbert Palka, Military Univ. of Technology (Poland); Anna B. Piotrowska, Institute of Electron Technology (Poland)

The AlGaAs/GaAs system is promising for THz QCLs. However, processing of these semiconductor structures into devices is still challenging. In particular, wafer bonding and fabrication of metallic layers are not trivial for QCLs with metal-metal (M-M) waveguides. This paper addresses these issues for a three-quantum-well design, with resonant-phonon depopulation of the laser's lower state. The QCL structure consists of 228 repeats of the following Al0.15Ga0.85As/GaAs single module: 45/87/29/83/44/159Å with barriers indicated in bold.

The basic processing steps included: fabrication of metallic layers, wafer bonding, removing the substrate and fabrication of the ridge structure. The M-M waveguides were used for modal confinement.

It is essential that the metallic layers allow to obtain ohmic contacts and low radiation losses. For M-M waveguide structures we modeled the influence of the composition and thickness of the metallic layers on the resulting electrical field distribution profile and the threshold gain. We chose Au-based and Cu–based M-M claddings for experimental investigation, particularly 5nmTi/300nmAu and 5nmTi/300nmCu. Good morphology and low roughness of 10nm for alloyed Ti/Au contact was revealed by TEM and AFM investigations. THz reflectance of these layers was bigger than 99%. The specific contact resistivity of 1.5?10-5 ? cm2 were calculated by CTLM method. During wafer bonding the most stable connection was obtained for comparable thickness of Au and In (~ 3um), for these thickness we created homogeneous AuIn alloy. This alloy is more reliable than AuIn2 or In.

These steps enabled fabrication of QCLs with current densities below 1,5kA/cm2, operating above cryogenic temperatures.

9199-3, Session 1

Broadly-tunable THz sources based on intra-cavity difference-frequency generation in mid-infrared quantum cascade lasers *(Invited Paper)*

Yifan Jiang, Seungyong Jung, Karun Vijayraghavan, Aiting Jiang, Mikhail A. Belkin, The Univ. of Texas at Austin (United States)

Widely-tunable room-temperature, electrically-pumped semiconductor sources in 1-5 THz spectral range are highly desired for spectroscopy and imaging application. THz sources based on intra-cavity difference-frequency generation (DFG) in dual wavelength mid-infrared quantum cascade lasers (QCLs) with Cherenkov phase-matching are currently the only monolithic room-temperature semiconductor devices that can operate and provide widely-tunable output in this entire spectral range and beyond. Here we will present our latest results on the development of broadly-tunable THz DFG-QCL systems. Our external-cavity broadly-tunable Cherenkov DFG-QCL devices bounded to undoped silicon substrates demonstrate continuously-tunable emission from 1.7 to 5.7 THz with 10 to 80 uW of THz peak power output at room temperature, depending on the spectral position, and virtually no THz beam steering. We will also discuss design and operation of monolithic THz DFG-QCL sources with electronic control of emission frequency.

9199-4, Session 1

Broadband THz quantum cascade lasers for comb applications *(Invited Paper)*

Giacomo Scalari, ETH Zurich (Switzerland); Markus Rösch, Mattias Beck, Jérôme Faist, ETH Zürich (Switzerland)

Frequency combs represent one of the most powerful tools in modern spectroscopy. In order to operate a frequency comb in the THz spectral region an active medium with a large gain bandwidth is highly desirable. We report here on a THz quantum cascade laser (QCL) which operates in continuous-wave (CW) with a bandwidth exceeding 1 THz with regular comb teeth and low threshold current density. The laser is based on a heterogeneous cascade design. It contains three different active region designs at central frequencies of 3 THz , 2.7 THz and 2.3 THz for a total active region thickness of 13.25 um.

The measured bandwidth in CW is 1 THz at -20 dB which corresponds to $\Delta f/f$ =36 % for a central frequency of 2.5 THz. At -40 dB we measure a bandwidth of 1.46 THz , corresponding to $\Delta f/f$=58%: the spectrum extends from 1.79 THz to 3.29 THz. The laser operates up to 105 K in pulsed and 50 K in CW. Lasing threshold lies at 210 A/cm2 in pulsed and at 260 A/cm2 in CW operation, and Jmax is 360 A/cm2. We will present also electrical and optical beatnote experiments aimed at clarifying the nature and the regime of comb operation.

9199-5, Session 2

Terahertz generation and picosecond photo-thermoelectric currents in graphene *(Invited Paper)*

Andreas Brenneis, Alexander Holleitner, Walter Schottky Institut (Germany)

We apply a time-domain THz spectroscopy to measure the ultrafast photocurrent response of optically pumped graphene [1]. To this end, a coplanar metal stripline circuit in combination with an on-chip pump/probe scheme is used. The striplines act as highly sensitive near-field

antennae with a bandwidth of up to 1 THz [2,3]. We find a THz response that we attributed to the coupling of the hot electron-hole plasma to coherent phonons [1], like it was observed in graphite [4, 5]. Our experiments further clarify the optoelectronic mechanisms contributing to the photocurrent generation at graphene-metal interfaces. We verify that both built-in electric fields, similar to those in semiconductor-metal interfaces, and a photo-thermoelectric effect give rise to the photocurrent at graphene-metal interfaces at different time scales. We particularly discuss how the picosecond photocurrents in graphene depend on the geometry and the thermal coupling of the devices to the environment [6].

We acknowledge the very fruitful cooperation with L. Prechtel, S. Manus, D. Schuh, W. Wegscheider, L. Song, P. Ajayan, L. Gaudreau, M. Seifert, H. Karl, H. Hübl, M. Brandt, F. Koppens, and J. Garrido.

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9199-6, Session 2

Efficient nonequilibrium Green's functions simulations of THz quantum cascade lasers

Mauro F. Fernandes Pereira Jr., Sheffield Hallam Univ. (United Kingdom); David Winge, Andreas Wacker, Lund Univ. (Sweden)

Electron-electron scattering is crucial for a realistic simulation of intersubband transport and optics in the THz range. Ideally it should be implemented with both frequency and momentum dependence, but this leads to a large computational effort. In this paper we discuss a new Nonequilibrium Green's Functions approach and the implementation of new set of approximations for electron-electron selfenergies which is part of a long term joint simulation effort. A number of systematic momentum approximations that simulate the full frequency are discussed and their impact on the transport (voltage vs current curves) and optical absorption and gain are presented. Good agreement with experimental data is found. A method to further extract effective electronic temperatures for comparison with experiments is discussed as well as a study of local inversion and gain.

9199-8, Session 2

Widely tunable THz-wave emitter with linear polarization characteristics based on antenna-integrated UTC-PD

Hiroshi Ito, Kitasato Univ. (Japan); Toshihide Yoshimatsu, NTT Network Innovation Labs. (Japan); Hiroshi Yamamoto, Kitasato Univ. (Japan); Tadao Ishibashi, NTT Photonics Labs. (Japan)

The photomixer-based terahertz (THz) wave emitter has several promising characteristics, such as extremely-wide frequency tunability, a very narrow line-width, good frequency stability, and the capability of low-loss signal transmissions through flexible optical fibers. In addition, the generation of frequency-independent linearly-polarized electro-magnetic waves is also important for some applications, such as imaging, spectroscopy, ellipsometry, and wireless data transmissions. In this regard, an appropriate design of the planar antenna integrated with the photomixer is essential.

To fulfill these requirements, we developed a photomixer integrating a novel self-complementary reflection-symmetry antenna with the uni-traveling-carrier photodiode (UTC-PD), and assembled it in a compact quasi-optical package. The fabricated module was operated at frequencies from 120 GHz to 2.6 THz, and the typical level of output power was 2.8 uW at 1 THz for a photocurrent of 9 mA at a bias voltage of only -0.4 V. It also exhibited stable principal polarization axis angles within ±1° at frequencies from 200 GHz to 2 THz, and the generated signals were linearly polarized with extinction ratios below 5 % at frequencies from 200 to 800 GHz. We also fabricated a quasi-optical Schottky barrier diode module with linear polarization characteristics, and these modules were applied to sub-THz-wave ellipsometry without using an external polarizer. We could successfully measure the complex relative dielectric constants of purified water as a test sample containing polar molecules.

9199-9, Session 3

TERA-MIR radiation: materials, generation, detection, and applications *(Invited Paper)*

Mauro F. Fernandes Pereira Jr., Sheffield Hallam Univ. (United Kingdom)

This talk starts by summarizing recent achievements of COST ACTION MP1204 [1], whose main objective is to advance novel materials, concepts and device designs for generating and detecting THz and Mid Infrared radiation using semiconductor, superconductor, metamaterials and lasers and to beneficially exploit their common aspects within a synergetic approach to unify these two spectral domains from their common aspects of sources, detectors, materials and applications. THz and MIR are considered jointly, the driving force for both regimes being applications in Physics, Electrical Engineering and Technology, Applied Chemistry, Materials Sciences and Biology and Radio Astronomy.

The second part of the talk delivers my own recent results. Starting with effective three dimensional anisotropic materials with new expressions for the nonlinear absorption, gain and luminescence of semiconductor superlattices described as anisotropic media and with applications to the luminescence of dilute nitride materials in excellent agreement with experiments. Next the superlattices are fully described in the case of Quantum Cascade Lasers (QCLs) and results of a cooperation between two teams of COST MP1204, which will lead to the new state of the art QCL simulators are outlined. Finally, the coupling of light in a microcavity with intersubband excitations considering both intervalence THz transitions [2] and dispersive gain with coupled polaritons and antipolaritons in dilut is investigated.

[1] http://www.tera-mir.org

[2] M.F. Pereira Jr and I.A. Faragai, Coupling of THz radiation with intervalence band transitions in microcavities, Editorially Accepted for Publication at Optics Express (2014).

9199-10, Session 3

Electromagnetic responses and ultrafast optical modulation of terahertz metamaterials

Qingli Zhou, Yulei Shi, Jianfeng Liu, Cunlin Zhang, Capital Normal Univ. (China)

Metamaterials with subwavelength structural features show unique electromagnetic responses that are unattainable with natural materials. Recently, the research on these artificial materials has been pushed forward to the terahertz (THz) region because of potential applications in biological fingerprinting, security imaging, and high frequency magnetic and electric resonant devices. Furthermore, active control of their properties could further facilitate and open up new applications in terms of modulation and switching. In our work, we will first present our

studies of dipole arrays at terahertz frequencies. Then in experimental and theoretical studies of terahertz subwavelength "L"-shaped structure, we proposed an unusual-mode current resonance responsible for low-frequency characteristic dip in transmission spectra. Comparing spectral properties of our designed simplified structures with that of split-ring resonators, we attribute this unusual mode to the resonance coupling and splitting under the broken symmetry of the structure. Finally, we use optical pump–terahertz probe method to investigate the spectral and dynamic behaviour of optical modulation in the split-ring resonators. We have observed the blue-shift and band broadening in the spectral changes of transmission under optical excitation at different delay times. The calculated surface currents using finite difference time domain simulation are presented to characterize these resonances, and the blue-shift can be explained by the changed refractive index and conductivity in the photoexcited semiconductor substrate.

9199-11, Session 3

Terahertz coded aperture mask using vanadium dioxide bowtie antenna array

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Terahertz imaging systems have received substantial attention from the scientific community for their use in astronomy, spectroscopy, plasma diagnostics and security. One approach to designing such systems is to use focal plane arrays. Although the principle of these systems is straightforward, realizing practical architectures has proven deceptively difficult. A different approach to imaging consists of spatially encoding the incoming flux of electromagnetic energy prior to detection using a reconfigurable mask. This technique is referred to as "coded aperture" or "Hadamard" imaging. This paper details the design, fabrication and testing of a prototype coded aperture mask operating at WR-1.5 (500-750 GHz) that uses the switching properties of vanadium dioxide (VO2). The switching array consists of bowtie antennas with vanadium dioxide VO2 elements at the feed points. From the symmetry, a unit cell of the array can be represented by an equivalent waveguide whose dimensions limit the maximum operating frequency. In this design, the cutoff frequency of the unit cell is 640 GHz. The VO2 devices are grown using reactive-biased target ion beam deposition. A reflection coefficient (S11) measurement of the mask in the WR-1.5 (500-750 GHz) band is conducted. The results are compared with circuit models and found to be in good agreement. A simulation of the transmission response of the mask is conducted and shows a transmission modulation of up to 28 dB. This project is a first step towards the development of a full coded aperture imaging system operating at WR-1.5 with VO2 as the mask switching element.

9199-12, Session 3

High-efficiency terahertz-wave generation in silicon membrane waveguides

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Terahertz (THz) wave generation via four-wave mixing (FWM) in silicon membrane waveguides is investigated with mid-infrared pump. The silicon membrane waveguides with width of 12 ?m and heights varied from 14 ?m to 17 ?m, which can confine the THz-wave ranging from 7.5 THz to 10 THz due to the large refractive index contrast of the waveguide core and cladding, are designed to realize the collinear phase matching for THz-wave generation via FWM. Compared with the conventional parametric amplification or wavelength conversion based on FWM in silicon waveguides, which needs a pump wavelength located in the anomalous group-velocity dispersion (GVD) regime to realize broad phase matching, the pump wavelength located in the normal GVD regime is required to realize phase matching because of the large signal-pump frequency detuning. Phase matching for a tunable THz-wave ranging from 8.57 THz to 10 THz can be realized by tuning the pump wavelength from 4.2 ?m to 4.4 ?m in the silicon waveguide with rib height of 15 ?m. Whilst, the phase matching bandwidth of THz-wave ranging from 7.7 THz to 10 THz can be achieved by tailoring the waveguide height from 14 ?m to 17 ?m when the pump wavelength is 4.3?m. Moreover, the conversion efficiency of the THz-wave generation is studied with different pump wavelengths and waveguide heights, the maximum conversion efficiency of 1.25 % at 9.2 THz can be obtained in a 6-mm long silicon waveguide when the pump wavelength is 4.3 ?m and the waveguide height is 15 ?m.

9199-13, Session 3

Transmission of THz pulse with a few circles through opaque samples placed at long distance (4-6 metres)

Vyacheslav A. Trofimov, Vladislav V. Trofimov, Lomonosov Moscow State Univ. (Russian Federation)

Nowadays, the detection and identification of dangerous substances at long distance (several metres, for example) by using of THz pulse reflected from the object is an important problem. In this report we demonstrate possibility of THz signal measuring reflected from a flat metallic mirror placed about 4 metres from the parabolic mirror of device. Investigated object is placed before additional flat mirror. Therefore, at present time our measurements contain features of both transmission and reflection modes. The reflecting mirror is used because of weak average power of used femtosecond laser. Measurements were provided at room temperature and humidity about 50%. The aim of investigation was the detection of a substance in real condition. We discuss new features of the detection of a substance covered under various ordinary materials and possible way for their influence deleting on the detection using reflected THz pulse.

9199-14, Session 4

Graphene plasmonic heterostructures for new types of terahertz lasers *(Invited Paper)*

Taiichi Otsuji, Victor Ryzhii, Stephane A. Boubanga Tombet, Takayuki Watanabe, Akira Satou, Tohoku Univ. (Japan); Maxim Ryzhii, Univ. of Aizu (Japan); Alexander A. Dubinov, Vladimir Y. Aleshkin, Institute for Physics of Microstructures (Russian Federation); Vyacheslav V. Popov, Kotelnikov Institute of Radio Engineering and Electronics (Saratov Branch), RAS (Russian Federation); Michael Shur, Rensselaer Polytechnic Institute (United States)

Graphene is a one-atom-thick planar sheet of carbon atoms that are densely packed in a honeycomb crystal lattice. The gapless and linear energy spectra of electrons and holes lead to nontrivial features such as mass-less relativistic transport of carriers called Dirac Fermions and hence the negative dynamic conductivity in the terahertz (THz) spectral range, which may lead to a new type of THz lasers. The two-dimensional Dirac Fermion systems in graphene yield unique plasmonic properties. We theoretically discovered and experimentally manifested that when graphene carrier populations are inverted by optical or electrical pumping the excitation of graphene plasmons by the THz photons results in propagating surface plasmon polaritons with giant gain in a wide THz range. When graphene is patterned in a micro- or nano-ribbon array by grating gate metallization, the structure acts as an active plasmonic metamaterial, providing a super-radiant plasmonic lasing with giant gain at the plasmon modes in a wide THz frequency range. Furthermore, double graphene layer heterostructures consisting of a tunnel barrier insulator sandwiched with a pair of gated graphene monolayers are introduced. Photon-assisted resonant tunneling can be electrically tuned to meet the graphene plasmon modes, resulting in enormous enhancement of the terahertz gain. Current injection structures are also addressed.

9199-15, Session 4

THz magnetospectroscopy of a CdTe/CdMgTe quantum point contact

Ignas Grigelionis, Marcin Bialek, Univ. of Warsaw (Poland); Marian Grynberg, University of Warsaw (Poland); Magdalena Czapkiewicz, Valery Kolkovski, Maciej Wiater, Michal Wojciechowski, Jerzy Wrobel, Tomasz Wojtowicz, Institute of Physics (Poland); Nina Diakonova, CNRS (France); Wojciech Knap, Univ. Montpellier 2 (France); Jerzy Lusakowski, Univ. of Warsaw (Poland)

In a quest to develop small detectors of THz radiation, we considered a structure invloving a quantum point contact (QPC) processed on a modulation - doped CdTe/CdMgTe single quantum well. A low-temperature mobility of the two-dimensional electron gas (2DEG) was on the level of 5x105 cm2/Vs. The QPC was defined with the electron lithography. Geometrically, the device showed a bottleneck shape where a 2 ?m - wide mesa narrowed to 460 nm in the QPC region. Lateral metallic gates, adjacent to the QPC, allowed to control the witdh of the conducting channel. Ohmic contacts allowed to investigate conductivity of the device. The sample was cooled to 1.8 K which made the device to work as a field-effect transistor with the threshold gate voltage of about -1.5 V. The sample was subject to a quantizing magnetic field (B), perpendicular to the 2DEG plane, and a THz radiation from a molecular laser. A photocurrent was measured as a function of the magnetic field at different THz photon wavelengths and the lateral gates polarization. The resulting spectra of the photocurrent vs magnetic field show a cyclotron resonance (CR) maximum with a rich structure of peaks at the the low-B shoulder of the CR. We interpret it as a series of magnetoplasmon modes. The frequency of the modes was quantitatively described with a dispersion relation of ungated magnetoplasmons with experimentally determined material parameters. In particular, the wavelength of the fundamental plasmon mode was equal to the width of the mesa of 2 ?m.

9199-16, Session 4

THz valence band polaritons and antipolaritons

Inuwa A. Faragai, Mauro F. Fernandes Pereira Jr., Sheffield Hallam Univ. (United Kingdom)

THz radiation is able to extract molecular spectral information in an otherwise inaccessible portion of the electromagnetic spectrum. Embedding devices in this range in microcavities can further improve their quantum efficiency and lead to new and interesting fundamental studies in many fields such as laser physics, cavity polaritons, optical control and on-chip quantum information processing. In this paper, we investigate THz polaritons and antipolaritons based on valence band transitions, which allow TE coupling in a simple configuration. The approach can improve the quantum efficiency of THz based devices based on TE mode in the strong coupling regime of THz radiations and intervalence bands transitions in a GaAs/AlGaAs quantum wells. A Nonequilibrium Many Body Approach for the optical response beyond the Hartree-Fock approximation is used as input to the effective dielectric function formalism for the polariton/antipolariton problem. The energy dispersion relations in the THz range are obtained by adjusting the full numerical solutions to simple analytical expressions, which can be used by non specialists in a wide number of new structures and material systems. The combination of manybody and nonparabolicity at high densities leads to dramatic changes in the polariton spectra in a nonequilibrium configuration, which is only possible for intervalence band transitions [1].

9199-17, Session 4

Terahertz waveguides with low transmission losses: characterization and applications *(Invited Paper)*

Oleg Mitrofanov, Univ. College London (United Kingdom); Miguel Navarro-Cia, Imperial College London (United Kingdom); Miriam S. Vitiello, Consiglio Nazionale delle Ricerche (Italy); Jeffrey E. Melzer, James A. Harrington, Rutgers, The State Univ. of New Jersey (United States)

Research in the area of THz waveguides has seen a rapid progress recently and has lead to demonstration of THz waveguides with transmission losses comparable to losses in air. We will overview approaches for achieving low transmission losses in THz waveguides and discuss dielectric-lined hollow metallic waveguides, which provide low attenuation (~1 dB/m) and relatively low dispersion (6 ps/THz/m).

Such low-loss waveguides require precise characterization of their transmission and modal properties. We will discuss the application of THz near-field microscopy in combination with the time-resolved pulsed THz spectroscopy for waveguide characterization. This technique has been shown to distinguish between normal waveguide modes and aid in mapping the mode spatial profiles in addition to characterization of the transmission loss and dispersion within the THz range.

One of the present challenging problems is waveguide integration with THz sources and detectors. We will discuss methods for achieving efficient coupling of THz waves to THz waveguides. We will also discuss directions for further development of the THz waveguides and their applications.

9199-18, Session 5

Magnetic-field tunable THz detectors based on GaAs/AlGaAs and CdTe/CdMgTe quantum wells *(Invited Paper)*

Jerzy Lusakowski, Marcin Bialek, Ignas Grigelionis, Univ. of Warsaw (Poland); Valery Kolkovski, Zbigniew Adamus, Institute of Physics (Poland); Marian Grynberg, Univ. of Warsaw (Poland); Jerzy Wrobel, Tomasz Wojtowicz, Grzegorz Karczewski, Institute of Physics (Poland); Valdimir Umansky, Weizmann Institute of Science (Israel)

Magnetic-field tunable cryogenic detectors are used in THz spectroscopy due to their sensitivity and possibility to respond to photons in a broad frequency range. Processes responsible for detection are optical transitions between quantum levels which separation can be changed by the magnetic field. Devices based on a cyclotron resonance (CR), i.e., a transition between Landau levels, belong to the most performant detectors of this type. A high mobility electron plasma offers a narrow CR line which allows to carry out precise spectroscopic THz measurements.

The aim of this study was to compare THz detectors processed on a high electron mobility GaAs/AlGaAs and CdTe/CdMgTe quantum wells. Transmission, photocurrent and photovoltage measurements were carried out as a function of the magnetic field at a constant energy of incident THz photons from monochromatic sources in the range 0.3 - 3 THz. The samples investigated were two-contact resistors or field-effect transisitors with the gate electrodes of different geometry: grid, meander or uniform. This allowed to investigate a THz response both of a gated and ungated plasma. The spectra show features resulting from three main processes: Shubnikov-deHaas oscillations, the cyclotron resonance and excitation of magnetoplasmons. Theoretical models allow to analyze quantitatively the frequency of observed excitations. The values of the electron effective mass and concentration used in the theoretical description were determined directly from experiments. This study allows to point at advantages and disadvantages of THz cyclotron-resonance detectors fabricated on GaAs- and CdTe-based quantum wells as well as to compare these two types of devices.

9199-19, Session 5

A high performance room temperature THz sensor

Janez Trontelj, Univ. of Ljubljana (Slovenia); Gintaras Valusis, Ctr. for Physical Sciences and Technology (Lithuania); Rimvydas Venckevicius, Center for Physical Sciences and Technology (Lithuania); Irmantas Kasalynas, Ctr. for Physical Sciences and Technology (Lithuania); Aleksander Sesek, Univ. of Ljubljana (Slovenia); Andrej Svigelj, Univ of Ljubljana (Slovenia)

In the paper THz antenna coupled microbolometer sensor is described. The concept of physical design optimization to minimize the device thermal losses and therefore to maximize its sensitivity is presented. Micromachining technology to fabricate a micro-meter bolometer sensor suitable for MEMS production is addressed, pointing out the key parameters for device optimization. The resulting device has very low volume of less than one cubic micrometer, and is therefore extremely sensitive. The challenge of designing the antenna to provide the maximal effective area and gain and the bolometer bias terminals design minimizing the influence on antenna properties is discussed. Many applications require frequency selectivity of the sensor to enable the multicolor THz imaging and spectroscopy applications. The technology for bolometer and antenna production is micromachining on silicon substrate which allows a simple and effective sensor array construction. The measured results of the sensor show impressive sensitivity and noise figures. The sensitivity of the sensor is up to 1000V/W and NEP down to 5pW /√Hz. The resonant THz antenna-coupled micro-bolometers were considered as a potential candidates for room temperature THz imaging as well as spectroscopic applications. Test samples of different chemical content – explosive simulators and medical drugs – were prepared and response in transsmission mode was measured. As the result composite homogeneity was screened and the average content of additives was estimated using the discrete-frequency spectroscopic THz imaging. In addition, possibility to use the micro-bolometer detectors linear array for beam profiling of wide-bandwidth THz source is discussed and experimental data is presented.

9199-20, Session 5

Emerging electronic devices for THz sensing and imaging *(Invited Paper)*

Patrick Fay, Yi Xie, Yuning Zhao, Zhenguo Jiang, Syed M. Rahman, Univ. of Notre Dame (United States); Huili Xing, Univ of Notre Dame (United States); Berardi Sensale-Rodriguez, Univ. of Utah (United States); Lei Liu, Univ. of Notre Dame (United States)

Continuing advances in scaling of conventional semiconductor devices are enabling mainstream electronics to operate in the millimeter-wave through THz regime. At the same time, however, novel devices and device concepts are also emerging to address the key challenges for systems in this frequency range, and may offer advantages. In addition to devices, advances in integration and system concepts also promise to provide substantial system-level performance and functionality enhancements. In this talk, several emerging devices and device concepts, as well as circuit-level concepts to take advantage of them, will be discussed. Based on unconventional semiconductor device structures and operational principles, these devices offer the potential for significantly improved system sensitivity and frequency coverage. When combined in novel planar arrays, features such as polariametric detection and frequency tunability for imaging can be achieved.

As examples of emerging devices for millimeter-wave through THz sensing and imaging, heterostructure backward diodes in the InAs/AlSb/GaSb material system and plasma-wave HEMTs in both InGaAs/InP and GaN-based material systems will be discussed. Based on interband tunneling, heterostruture backward diodes offer significantly increased sensitivity and extremely low noise for direct detection applications, and have been demonstrated with cutoff frequencies exceeding 8 THz. The plasma-wave HEMTs is an emerging device concept that, by leveraging plasma-wave resonances in the 2DEG channel of a HEMT, offers the prospect for both tunable narrowband detection as well as low-noise amplification at frequencies well into the THz. These emerging devices are both amenable to direct integration within compact planar radiating structures such as ring-slot antennas for realization of polariametric detection and frequency tuning for spectroscopy and imaging.

9199-21, Session 6

THz QCL self-mixing interferometry for biomedical applications *(Invited Paper)*

Aleksandar D. Rakic, Thomas Taimre, Karl Bertling, Yah Leng Lim, Stephen J. Wilson, The Univ. of Queensland (Australia); Paul Dean, Dragan Indjin, Edmund H. Linfield, A. Giles Davies, Univ. of Leeds (United Kingdom)

The imaging of structures within the superficial layers of skin has become a major approach for detecting skin conditions in the developed world. Terahertz (THz) frequency radiation is particularly well suited for biological imaging due to its sensitivity to water content, a consequence of the high absorption of THz radiation in water. However, to date, general adoption of THz radiation for biological applications has been adversely affected by the absence of a compact, inexpensive sensing solution.

Over the past decade, the quantum cascade laser (QCL) has established itself as one of the most promising radiation sources for imaging applications at THz frequencies due to its ability to generate coherent continuous-wave emission with quantum noise-limited linewidths. This makes THz QCLs particularly suited to the development of coherent THz sensing and imaging systems.

In this paper, we introduce the self-mixing (SM) phenomenon in QCLs and then present recent advancements in the development of coherent THz imaging and sensing systems that exploit the SM effect. We present an imaging and tissue analysis scheme in the THz which exploits the interferometric nature of optical feedback in a THz QCL to employ it as a homodyning transceiver. This results in a highly sensitive and compact scheme. We apply this scheme to the imaging of excised tissue, and present a range of high-contrast THz images through different reductions of the information-rich interferometric signals. In these images, clear contrast between different tissue types is observed, corresponding to differing interferometric signal morphology.

9199-22, Session 6

Use of terahertz radiation for non destructive testing of composite materials of aircrafts

Nikolay S. Balbekin, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Evgeny Novoselov, Chalmers Univ. of Technology (Sweden); Pavel V. Pavlov, Irkutsk Military Aviation Engineering Institute (Russian Federation); Nikolay V. Petrov, Victor G. Bespalov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

In this paper we consider using the terahertz time domain spectroscopy (THz TDS) for non destructive testing and determining the chemical composition of the blades and blade spars of aircrafts propellers and other composite material products. A versatile terahertz spectrometer for reflection and transmission has been used for experiments. Measurements were carried out 10 times for each sample. We consider the features of measured terahertz signal in temporal and spectral domains during propagation through and reflecting from various defects in investigated objects, such as voids and foliation. We discuss requirements are applicable to the setup and are necessary to produce an image of these defects, such as signal-to-noise ratio and a method for registering THz radiation.

The observed peculiarities in the signal characteristics are illustrated by results of numerical modelling of propagation process of broadband THz radiation through the investigated samples. Mathematical model, which is used for numerical simulation, is based on methods of scalar diffraction theory and decomposition of broadband THz radiation to the assembly of monochromatic components. Obtained results indicated the prospects of the THz TDS method for the inspection of defects and determination of the particularities of chemical composition of aircraft parts.

9199-23, Session 6

Expectation maximisation algorithms for terahertz transmission tomography

Benoit Recur, The Australian National Univ. (Australia); Hugo Balacey, Lab. Ondes et Matière d'Aquitaine (France) and Noctylio S.A.S (France); Patrick Mounaix, Univ. Bordeaux 1 (France)

In the field of non-destructive testing, Terahertz (THz) tomography is a recent imaging technique allowing 3D inspection of opaque objects. Several radiographs are acquired around the sample at different viewing angles. Then a tomographic algorithm reconstructs a 3D volume imaging the object from data contained on the projection set. Low energy of THz waves provides a high contrast imaging of small-size and low density samples. This property has made THz tomography a complementary technique since such samples provide a low contrast resolution using X-Rays.

Several reconstruction methods have been investigated for THz tomography, but they are not adjusted to THz wave properties. In the case of monochromatic source, the attenuation encountered by THz waves through the sample and measured on the detector is modelled by Beer-Lambert. Then, as their counterparts in X-Ray tomography, we investigate on an expectation-maximization reconstruction algorithm for THz imaging (THz EM-TR) based on such a model.

Moreover in X-Ray tomography, dual-energy reconstructions based on global attenuation modelling allow to estimate physical properties (atomic number and density distributions) from two acquisitions at different energies. To our own knowledge, such a process has not been applied in THz tomography. However X-Ray applications demonstrated an improved reconstruction and a correct material characterisation using this approach. Thus we also investigate on a THz wave attenuation model and a dual-energy THz EM-TR reconstruction. Using data acquired with a dual-energy 100/300GHz scanner, we explore how this new reconstruction is able to extract sample physical properties in addition to the 3D reconstruction.

9199-24, Session 6

Resolution enhancing of commercially available passive THz cameras due to computer processing

Vyacheslav A. Trofimov, Vladislav V. Trofimov, Igor E. Kuchik, Lomonosov Moscow State Univ. (Russian Federation)

We demonstrate new opportunities for the detection of concealed objects and of clothes components due to using of computer processing of images captured by passive THz cameras, manufactured by various companies. Computer processing of images results in a temperature resolution enhancing of cameras. We achieve good quality of the image due to applying various spatial filters to show independence of processed images on math operations. This result demonstrates a validity of observable objects.

We discuss also a possibility of temperature trace observing on human skin if there is a difference in temperature inside the body.

We consider images produced by THz passive cameras manufactured by Microsemi Corp., and ThruVision Corp., and Capital Normal University (Beijing, China).

9199-25, Session 6

THz imaging studies of lead white-painted plaster samples to guide cultural heritage investigations at the cell of St. Neophytos in Paphos, Cyprus

Roxanne Radpour, Bryan Nowroozi, Univ. of California, Los Angeles (United States); Neha Bajwa, Ctr. for Advanced Surgical and Interventional Technology (United States); James Garritano, Shijun Sung, Magdalena Balonis, Univ. of California, Los Angeles (United States); Priyamvada Tewari, Ctr. for Advanced Surgical and Interventional Technology (United States); Warren Grundfest, Ioanna Kakoulli, Zachary D. Taylor, Univ. of California, Los Angeles (United States)

Terahertz (THz) imaging is a relatively new non-destructive analysis technique that is transitioning from established application research areas such as defense and biomedicine to studies of cultural heritage artifacts. Our research adopts a THz medical imaging system, originally designed for in vivo hydration sensing, to acquire high contrast imagery of painted plaster samples. These are mock-ups mimicking the Byzantine wall paintings at the cell of St. Neophytos in Paphos, Cyprus. The original 12th century paintings show evidence of later painting phases overlapping the original iconography. A thin layer of lead white (2PbCO3·Pb(OH)2) underlies the visible wall paintings, suggesting that earlier works are concealed beneath. Both traditional imaging modalities and standard THz imaging techniques have been unable to image this concealed iconography due to a combination of absorption and scattering. We aim to use THz imaging and novel optical design to probe beyond the visible surface and perform in situ analysis of iconography beneath the lead white layer. Imaging results of pigments deposited on top of plaster mock-ups and obscured with lead white are presented and contrast sufficient for identification is demonstrated. Additionally, narrowband spectroscopic measurements are presented and their application to optimal system design discussed. These preliminary studies show potential for imaging pigments beneath lead white. The analysis performed of THz scattering within paint and plaster materials provides a path towards improving spatial resolution? and penetration depth in THz imaging systems, and the plaster samples imaged closely reflect real world conditions, thus justifying in situ analysis within the Enkleistra.

9199-26, Session 7

First experimental investigation of selectivity in THz biospectroscopy *(Invited Paper)*

Elliott R. Brown, Weidong Zhang, Leamon Viveros, Wright State Univ. (United States)

With the recent detection of strong THz signatures from bacterial spores (genus bacillus), the possibility exists to establish for the first time selectivity in the THz spectroscopy of biological macromolecules and bioparticles. This paper will examine the issue of sensitivity and selectivity between the spores of two similar species: Bacillus thuringiensis (or Bt), and Bacillus cereus (or Bc) when detected alone and combined in mixtures. The primary mechanism for THz signatures in these spores – low-lying optical-phonon polaritons – will be reviewed and further examined in the context of sensitivity and selectivity. A key issue in this endeavor is the dependence of the THz signatures on environmental conditions, such as hydration and pH, and on clutter.

9199-27, Session 7

THz optical design considerations and optimization for medical imaging applications

Shijun Sung, James Garritano, Neha Bajwa, Univ. of California, Los Angeles (United States); Bryan Nowroozi, Ctr. for Advanced Surgical and Interventional Technology (United States); Priyamvada Tewari, Warren Grundfest, Zachary D. Taylor, Univ. of California, Los Angeles (United States)

Optical design considerations for THz medical imaging must account for practical performance characteristics of THz sources and detectors as well as the target geometry and parameters. This study presents analysis of several novel THz optical designs that enable quick interchanges of THz beam parameters without disturbing rest of the fixed optics, allowing the user to easily and quickly explore effects of optical parameters such as such as illumination spot size, depth of focus (DOF), and polarization. This is key to animal trials where alignment time can become quite costly. We report characterization and performance of THz objective mirror design employing pairs of off-axis parabolic (OAP) mirrors with effective focal length of 25.4mm, 50.8mm, and 76.2mm.. We demonstrate diffraction limited spot size and observe that the DOF with this optical train is a combined outcome of the sensitivity of 90o OAP mirrors to axial alignment and the finite aperture size of the detector. This results in beam walk-off at the detector plane yielding confocal-like operation. While this design achieves sufficient performance metrics, simulations revealed inherent field profile and polarization distortions introduced by off-axis parabolic mirrors. To correct for these aberrations and prepare for clinical imaging a beam-scanning system is designed with compensating mirror orientations. Simulations demonstrate that appropriate mirror orientation cancels out aberrations and allows for 1 dimensional scanning with a constant THz path length. Images of phantom and animal models acquired with these geometries are presented.

9199-28, Session 7

THz-TDS combined with a fuzzy rule-building expert system applied to identification of official rhubarb samples

Zhuo-yong Zhang, Yi Liao, Xia Zuo, Jingrong Wang, Zhenwei Zhang, Capital Normal Univ. (China); Peter Harrington, Ohio Univ. (United States)

Rhubarb has a long history and high medicinal value as a well-known traditional medicinal material in China. The dried rhizome and roots of Rheum palmatum L, Rheum tanguticum Maxim. ex Balf, and Rheum officinale Baill are three kinds of official rhubarb in the Chinese Pharmacopoeia. Terahertz time-domain spectroscopy (THz-TDS) technology as a new non-destructive testing method has been applied to identify 41 official and unofficial rhubarb samples in the present work. The THz time domain spectra of rhubarb samples were preprocessed and then used to establish an identification model by using fuzzy rule-building expert systems (FuRES). The model was validated using bootstrapped Latin-partitions (BLPs) method with 10 bootstraps and 4 Latin-partitions. The obtained results showed that the model has good predictive ability with respect to the classification accuracy of 94.8±0.5% and 95.2±0.1% by using the preprocessing methods of Savitzky-Golay (S-G) first derivative combined with either one of two orthogonal signal correction (OSC) methods, respectively. The proposed method showed that the THz-TDS combined with chemometrics can be used to identify genuine and counterfeit Chinese herbal medicines, as well as official and unofficial rhubarbs.

In this paper, THz-TDS system was applied to measure the spectra of 41 rhubarb samples at room temperature. The different preprocessing methods combined with FuRES were used to establish the qualitative analysis model for the recognition of official and unofficial rhubarb. The obtained results showed that the methods of S-G first derivative combined with EOSC and PC-OSC gave good predictive ability, with classification accuracies of 94.8 ± 0.5% and 95.2 ± 0.1% were achieved respectively, which were significantly better than the results obtained by other pretreatment methods. The PC-OSC gave better results in that a higher prediction rate was achieved using less than half the components that were required for the EOSC method. The proposed method is a simple, fast, solvent free, and environmentally friendly method that could be employed to identify official and unofficial rhubarb. The above method can also be used for quality control in the production of other Chinese herbal medicines.

9199-29, Session 7

In vivo confirmation of hydration based contrast mechanisms for THz medical imaging using MRI

Neha Bajwa, Ctr. for Advanced Surgical and Interventional Technology (United States); Shijun Sung, James Garritano, Bryan Nowroozi, Univ. of California, Los Angeles (United States); Priyamvada Tewari, Ctr. for Advanced Surgical and Interventional Technology (United States); Daniel B. Ennis, Jeffery Alger, Zachary D. Taylor, Warren Grundfest, Univ. of California, Los Angeles (United States)

Terahertz (THz) detection has been proposed and applied to a variety of medical imaging applications in view of its unrivaled hydration profiling capabilities. Variations in tissue dielectric function have been demonstrated at THz frequencies to generate high contrast imagery of tissue, however, the source of image contrast remains to be verified using a modality with a comparable sensing scheme. To investigate the primary contrast mechanism, a pilot comparison study in an in vivo burn wound rat model, widely known to create detectable gradients in tissue hydration through both injured and surrounding tissue, was performed. Parallel T2 weighted multi slice multi echo (T2w MSME) 7T Magnetic Resonance (MR) scans and THz surface reflectance maps were acquired of a full thickness skin burn in a rat model over a 5 hour time period. A comparison of uninjured and injured regions in the full thickness burn demonstrates a 3-fold increase in T2 relaxation times and 15% increase in average THz reflectivity, respectively. These results support the sensitivity and specificity of MRI for measuring burn tissue water content and the use of this modality to verify and understand the hydration sensing capabilities of THz imaging for acute assessments of the onset and evolution of diseases that affect the skin and eye. These preliminary analyses serve as a starting point for more sophisticated in vivo studies that will explore how and to what extent the release of unbound water affects imaging contrast in THz burn sensing.

9199-30, Session 7

THz dielectric substrate window optimization for hydration sensitivity

James Garritano, Neha Bajwa, Shijun Sung, Bryan Nowroozi, Priyamvada Tewari, Roxanne Radpour, Warren Grundfest, Zachary D. Taylor, Univ. of California, Los Angeles (United States)

Variations in the distribution of water along the coronal axis have been investigated as a source of contrast in several reflective THz medical imaging applications, including corneal hydration sensing and burn wound severity diagnosis. Dielectric substrate windows used in reflective THz imaging applications create frequency-dependent interference effects, which depend on the window's optical path length and the specimen's hydration distribution. Windows increase a system's sensitivity to certain hydration distributions, while decreasing others. To investigate these interference effects we implemented an electromagnetic model that computes sensitivity metrics given the window and specimen population. Experimental results with varying windows are presented.

9199-31, Session 8

Graphene: a perfectly unexceptional nonlinear material *(Invited Paper)*

Jacob B. Khurgin, Johns Hopkins Univ. (United States)

In the last decade graphene has become a focus of attention in many areas of electronics and optics, including the nonlinear optics. It has been almost universally assumed that Dirac-like dispersion of electrons and holes endows graphene with a unique set of nonlinear optical properties, vastly superior to the more conventional nonlinear materials, especially in the THz and far infrared range of spectrum. We have rigorously examined the nonlinear optical properties of graphene and have concluded that it indeed can exhibit very high values of nonlinear index of refraction in both intra-band and band-to-band transitions at low power densities, but when it comes to true figures of merit, i.e. the ability to achieve all optical switching or high efficiency frequency conversion, graphene's advantages ebb due to high absorption, and, rather unexpectedly , due to saturation of nonlinearity. In this talk we consider the figures of merits as functions of doping density, geometry, and wavelength and define the application niches where graphene may be used

9199-32, Session 8

Resonant nonlinearities in quantum cascade lasers *(Invited Paper)*

Sukhdeep S. Dhillon, Ecole Normale Superieure (France)

The nonlinear optical properties of intersubband and interband transitions in quantum wells has received considerable attention owing to their enhanced nonlinear susceptibilities compared to the bulk characteristics. Indeed efficient non-linear wave mixing between a near-infrared interband probe in presence of an intense terahertz (THz) beam (intersubband resonance) in quantum wells has been previously demonstrated. However, the THz radiation is typically provided by a Free Electron Laser that strongly limits its relevance to applications. Here we demonstrate that these types of high order nonlinear processes can be realized using the resonant nonlinearities within a compact and practical device – the quantum-cascade-laser.

9199-33, Session 8

Novel THz applications: from Bragg gratings waveguide sensors to nanoparticle-based imaging *(Invited Paper)*

Anna Mazhorova, Matteo Clerici, Rafik Naccache, Manoj K. Mridha, Luca Razzari, Fiorenzo Vetrone, Roberto Morandotti, Institut National de la Recherche Scientifique (Canada)

During the past decade, various Terahertz technologies were successfully implemented in THz sensing and imaging for chemical, biological, biomedical and other interdisciplinary study. Two-wire waveguides, due to their low dispersion, broadband guiding characteristic and two-dimensional confinement, offer an excellent THz guiding medium. We demonstrate a novel kind of low-loss, high coupling efficiency THz waveguide Bragg grating–resulting from the combination of a low-dispersion two-wire waveguide and a low-loss polymer mesh. Such a waveguide structure allows enhancement of the spectral lines due to the so-called slow light effects, making it a promising candidate for future sensors with enhanced sensitivity.

Furthermore, the rapid ascent of nanoscience has garnered significant attention in recent years. Much of the interest generated has dealt with the use of Gold Nanorods (GNRs) in imaging and therapeutics. GNRs show a surface plasmon resonance (SPR) following the excitation with an appropriate irradiation source. A fascinating by-product of SPRs is a localized temperature increase, which can be used to heat the interstitial waters and induce hyperthermia in cells. We study the use of THz waves for temperature sensing and imaging in vitro, given the sensitivity of the THz waves to changes in the absorption and the refractive indices of water and other aqueous media. We have shown that THz waves can be used for temperature sensing in the biological temperature window of 25-60 °C. Combined with sensitive imaging capacities, and localized plasmonic heating, the proposed technique can be further extended to applications in skin cancer therapy.

9199-34, Session PMon

Visible-light controlled plasma excitations in high electron mobility GaAs/AlGaAs heterostructure

Marcin Bialek, Dmitriy Yavorskiy, Michal Marcinkiewicz, Tomasz Tarkowski, Univ. of Warsaw (Poland); Jerzy Wrobel, Institute of Physics (Poland); Vladimir Umansky, Weizmann Institute of Science (Israel); Barbara Pietka, Jerzy Lusakowski, Univ. of Warsaw (Poland)

Plasmonic detectors processed on a high-electron mobility GaAs/AlGaAs heterostructure were investigated at 4 K at fields up to 10 T. The detectors were exposed to THz radiation in the range 330 - 660 GHz and could be additionally illuminated with a visible laser light. Transport measurements allowed to determine the electron concentration by measurements of the Shubnikov-de Haas oscillations. The detectors were fabricated on a 0.06 mm x 1.3 mm mesas etched in a 4 mm x 4 mm pieces of the heterostructure characterized by the electron mobility and concentration of about 3x1011 cm-2 and 4x105 cm2/Vs at 4 K, respectively. The detectors were of a field-effect transistor design with Au/Ge/Ni ohmic source and drain contacts and a Au/Ti gate which formed the shape of a meander. The period of the meander was 8 ?m.

A THz response of the detector showed the cyclotron resonance transition accompanied with a series of magnetoplasmon excitations which position in the magnetic field was quantitatively described by a dispersion of ungated magnetoplasmons. The frequency of the fundamental mode was determined by its wavelength equal to the width of the mesa and the experimentally determined electron concentration. Illumination with a visible light caused a permanent change in the magnetoplasmon spectrum which were investigated as a function of the light wavelength and intensity. A long-term stability of the THz response after the illumination was also investigated. Thus we showed that a visible light can be used to modulate THz response of plasmonic detectors at low temperatures.

9199-35, Session PMon

Mid infrared luminescence of dilute nitride semiconductors: microscopic approach vs experiments

Chijioke I. Oriaku, Mauro F. Fernandes Pereira Jr., Sheffield Hallam Univ. (United Kingdom)

Luminescence plays a major role in fundamental studies and one of the main characterization tools of new materials and optoelectronic devices. In this paper we deliver an accurate analytical approximation for luminescence that can be easily programmed and includes the main many body effects required to describe bulk semiconductors. The Kubo Martin Schinger (KMS) relation is used to deliver expression that is based on formula for the optical susceptibility and absorption that reduce exactly to Elliott's formula in the low density limit, in contrast to previous results in the literature. This leads to a very powerful tool to investigate new materials, starting e.g. from ab initio calculations and has potential for a major impact in the development of new bulk materials for efficient solar cells and for mid infrared radiation generation and detection. A detailed comparison with recently grown mid infrared emitting InAsN structures clearly shows the power and accuracy of the expressions.

9199-36, Session PMon

Experimental imaging research on continuous-wave terahertz in-line digital holography

HaoChong Huang, Dayong Wang, Lu Rong, Yunxin Wang, Beijing Univ. of Technology (China)

Terahertz (THz) imaging is an advanced technique that can be applied in varied fields. Due to its noncontact, noninvasive and high-resolution capabilities, it has already shown great application prospects in biomedical observation, sample measurement, and quality control. The continuous-wave THz in-line digital holography is a combination of THz technology and digital holography of which the source is THz laser. Over the past decade, researchers used different THz sources and detectors to undertake the experiments. The THz laser is an integrated CO2 and FIR laser system (FIRL100, Edinburgh Instrument Ltd.). The frequency of the THz wave is 2.52 THz (wavelength of 118.83 ?m). And output power of THz laser in the experiment is set at 120 mW. The pyroelectric camera (Pyrocam III, Ophir-Spiricon, Inc.) is used to record the interference patterns. The camera's pixel number, size and pitch are 124 ? 124 pixels, 85 ?m ?85 ?m, and 100 ?m ?100 ?m, respectively. The pin which THz wave can't penetrate and the TPX slice carved "THz" are chosen for the samples. Via the pyroelectric camera's collection, we have got 1000 inference patterns, and the process of the holograms' accumulation and normalization is accomplished. Then the hologram propagates back to the object plane using the angular spectrum propagation integral in the computer to acquire the reconstruction images. In order to eliminate the twin images in reconstruction results, the iteration algorithm method is applied to data analysis. Finally the complex amplitude of the samples is obtained in the experiment.

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9200-1, Session 1

Design and performance of optical materials by manipulating nano and micromorphology

(Invited Paper)

Narsingh B. Singh, Univ. of Maryland, Baltimore County (United States); Narasimha S. Prasad, NASA Langley Research Ctr. (United States); Bradley Arnold, Lisa Kelly, Brian M. Cullum, Univ. of Maryland, Baltimore County (United States)

Since more than a decade huge number of papers have been published. Applications for RF applications has been limited due to very large absorption. Design of metamaterials for optical applications has great promise if one can design materials without using metal layer in the system. This paper describes morphologies of optical materials.

9200-2, Session 1

Elaborations on surface structural effects, electrical surface resistivity, and optical waveguide properties of gadolinium oxide (Gd2O3) and gadolinium oxide europium doped (Gd2O3:Eu3+) sol-gel films

Quianna S. Johnson, Matthew E. Edwards Sr., Michael J. Curley, Alabama A&M Univ. (United States)

In this research, the authors give an analysis of surface structural morphology, the electrical surface resistivity and optical waveguide properties of gadolinium oxide (Gd2O3) and gadolinium oxide europium doped (Gd2O3:Eu3+) films as prepared via the sol-gel and dip coating methods under atmospheric and clean room conditions. After describing sol-gel preparation routines, the authors further give observations of homogeneous surface morphological as characterized with scanning electron microscope (SEM) techniques. In addition, electrical surface resistivity measures have been made with Keithley 6517B Electrometer when interfaced with Keithley model 8009 resistivity test fixture, and optical waveguide propagation has been described of such Gd2O3 and Gd2O3:Eu3+ films. The samples' structural, electrical surface resistivity and resulting optical properties, in waveguiding configuration, were studied and compared according to film thickness and surface morphological features.

9200-3, Session 1

Helical auto-waves electron-hole plasma in semiconductor induced by femtosecond pulse at presence of external electric field

Vyacheslav A. Trofimov, Vladimir A. Egorenkov, Mariya M. Loginovaa, Lomonosov Moscow State Univ. (Russian Federation)

We analyze laser-induced periodic structure developing in a semiconductor under both femtosecond pulse acting and external electric field acting. Optical bistability appears because of nonlinear dependence of semiconductor absorption coefficient on charged particles concentration caused by both the Fermi energy level renormalization and the Burstein-Moss effect. The electron mobility, diffusion of electrons, and laser-induced electric field are taken into account for laser pulse propagation analyzing.

We found out that an external electric field could induce helical auto-waves of high absorption domain in semiconductor. These waves take place for an external electric field, which is constant in time or it varies in accordance of periodic law in time.

We consider also the helical auto-waves developing in semiconductor if an external electric field changes periodically in spatial coordinate along which a femtosecond pulse propogates.

9200-4, Session 1

Mode dependent pump absorption in the double cladding fiber considering the mode diffusion

Zhihua Huang, Xiaocheng Tian, Dangpeng Xu, Honghuan Lin, Jianjun Wang, China Academy of Engineering Physics (China)

In double-cladding rare earth doped fibers, there is considerable discrepancy between the actual pump absorption and the exponential decay which is called the Beer's law. The coupled mode theory including the mode diffusion effect is developed to take the disturbance of the micro-bending and non-uniformity of the fiber into account. This theory can be applied for precise analysis and optimization of the pump absorption in the high power large-mode-area fiber lasers. Tapered fiber with decreasing inner cladding diameter is proposed for full pump absorption.

9200-5, Session 1

Formation of sub pico-liter liquid periodic structure in a hollow optical fiber for photonic device applications

Jihyun Hwang, Jongki Kim, Jiyoung Park, Kyunghwan K. Oh, Yonsei Univ. (Korea, Republic of)

We report a unique technique to generate a liquid periodic structure whose unit volume is as low as a few hundred femto-liter. Liquids such as water, toluene and ethanol were filled in a hollow optical fiber (hole diameter of 8 and13?m), which were locally heated by a traversing miniature electric furnace. The periods between droplets could be varied flexibly in the range from 14 to 100?m and the volume of individual droplet was in the range from 112 to 845 femto-liter. We also fabricated the periodic liquid droplets with quantum dots, whose fluorescence was successfully measured in each droplet. These periodic liquid droplets could serve as flexible liquid long period fiber grating for the hollow optical fiber, which can be further applied in various mechanical and bio-chemical sensors

9200-6, Session 1

Fabrication of transparent transistor by using nitrogen-doped SnO2 P-type transparent conducting thin film

Po-Ming Lee, Albert T. Wu, National Central Univ. (Taiwan)

Like the most TCOs (transparent conducting oxide), the carrier polarity of the un-doped SnO2 is n-type. It has been reported that, by substituting IIIA elements (Al, Ga, In) with the Sn sites, the carrier polarity of the doped-SnO2 can transform from n-type to p-type. Besides doping

metallic cations into SnO2 phase, Pan et at. found that p-type SnO2 can also be achieved by doping nitrogen in SnO2 as anionic substitution. In this work, we made an attempt to co-dop the metallic cations and N anion into the SnO2 phase to enhance the electrical property of the p-type SnO2. The preliminary results show that several p-type SnO2-based thin films indeed can be achieved by doping nitrides (AlN, TiN, Si3N4) into SnO2 thin films. The nitride-doping process was done by RF magnetron sputtering system. The developed p-type SnO2 thin films have a high transmittance (over 80%) in the visible region. The lowest resistivity of the nitride-doped SnO2 thin film can be below 0.2 (Ω-cm) with a high carrier concentration of 1.52 E19 (cm-3).

By using these developed p-type SnO2 thin films as the channel layer, we successfully fabricated thin film transparent transistors. The electrical property of the transistors was measured by the 4200-scs semiconductor parameter analyzer. The preliminary results show that the field effect mobility and subthreshold swing were found to be 2 E-2 (cm2/V-s) and 3.7 (V/dec). The detail electrical characteristics of the p-type SnO2 thin films and the thin film transistors would be presented in this talk.

9200-7, Session 1

Transparent p+-TiN:SnO2/n+-ITO tunnel diode

Chih-Yi Hsieh, Chin-Han Liao, Cheng-Yi Liu, National Central Univ. (Taiwan)

Many invisible electronic devices have been developed in recent years, such as, transistors and p-n junctions. Yet, so far, no transparent tunnel diode has ever been reported. In this work, we demonstrate an unique approach to fabricate a transparent p+-TiN:SnO2/n+-ITO tunnel diode. The p+-TiN:SnO2 thin film formed by annealing a SnO2/TiN multi-layer structure. The hole carriers in the p+-TiN:SnO2 thin film are mainly generated by the N3--O2- substitution reaction. The p+-TiN:SnO2 thin film has low resistivity (0.2 ?•cm) and high hole concentration (1.52?1019 cm-3). The I-V characteristics of the p+-TiN:SnO2/n+-ITO junction exhibits distinct tunnel diode characteristics. In addition, the overall transmittance of the p+-TiN:SnO2/n+-ITO tunnel diode is higher than 80% in the visible region. The transparent p+-TiN:SnO2/n+-ITO tunnel diode can be further applied in transparent tunnel field-effect transistor (TFET) and other invisible electronics.

9200-8, Session 1

A compact in-situ ellipsometer using the liquid crystal phase retarder

Wen-Tse Shih, Minghsin Univ. of Science and Technology (Taiwan); Mei-Li Hsieh, Yu Faye Chao, National Chiao Tung Univ. (Taiwan)

The ellipsometry features mainly in characterizing the optical properties of materials, such as the complex refraction index, thickness, and surface roughness. The main advantages of applying the ellipsometer to the studies concerning material science are non-contact and non-destructive scheme, high sensitivity, and various samples, i.e., bulk materials, liquids, the surfaces of solids, and multi-layered thin films. The in-situ ellipsometer is helpful to many applications, for example, the sample condition monitoring in the film deposition or etching system. For observing dynamic processes of samples, the photoelastic modulator has been widely used in the real time ellipsometric system. In this paper, we proposed a compact in-situ ellipsometer using a commercial liquid crystal (LC) phase retarder. Utilizing the LC retarder, the polarization state of the beam can be manipulated with a switching frequency more than one hundred hertz, which makes the ellipsometer suitable for real-time measurements. Since the accuracy of an ellipsometer depends on the alignment of each optical component in the system, we demonstrate an alignment calibration procedure of the in-situ ellipsometer, including the polarizer, analyzer and LC retarder. All the calibrations are based on the three-intensity measurement technique, which makes the procedure precise, efficient and reliable. Finally, we will present and discuss the experimental results of our system.

9200-9, Session 1

Optical characterization of ferroelectric PZT thin films by variable angle spectroscopic ellipsometry

Md. Shafiqur Rahman, Carlos D. Garcia, Amar S. Bhalla, Ruyan Guo, The Univ. of Texas at San Antonio (United States)

Ferroelectric thin films are used as high dielectric constant capacitors, infrared detectors, piezoelectric transducers, optical modulators, optical waveguides, and nonvolatile memory chips for dynamic random access memory (DRAM) etc. While ferroelectric and dielectric properties of these films have been extensively investigated, their optical properties have been comparatively less studied and of limited use in quantitative evaluation of multilayer thin films. In this work we explored the variable angle spectroscopic ellipsometry (VASE) technique for its effectiveness in physical property characterization. The VASE combined with its computer modeling tool enables nondestructive, nonintrusive, and contactless optical means for optical characterization. Crystalline Lead Zirconium Titanate PbZr_0.52 Ti_0.48 O_3 (PZT) thin films, fabricated on SrTiO_3 layer atop of Si substrates, were characterized using VASE (J.A. Woollam; Lincoln, NE, USA) by determining the ellipsometric parameters ? and ? as a function of wavelengths (200-1000 nm) and incident angles (?65?^0,?70?^0,?75?^0) at room temperature. A physical representation of the multilayer system was constructed by a six layer model (analysis software WVASE32, J.A. Woollam) through a step-by-step method. Other physical properties characterized by several well-known techniques on structure, morphology and topographical features correspond well with the models developed using VASE alone. The technique and the methodology developed have shown promises in identifying the respective thickness and optical properties of multilayer thin film system, with limited input of processing or composition informations.

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9200-10, Session 2

Efficient upconversion polymer-inorganic nanocomposite thin film emitters prepared by the double beam matrix assisted pulsed laser evaporation (DB-MAPLE) method *(Invited Paper)*

Abdalla M. Darwish, Siemon Wilson, Ashley Blackwell, Keylantra Taylor, Dillard Univ. (United States); Sergey S. Sarkisov, SSS Optical Technologies, LLC (United States); Brent Koplitz, Tulane Univ. (United States)

We report on fabrication and investigation of optical and morphological properties of highly efficient (a quantum yield of 1%) upconversion polymer-inorganic nanocomposite thin film emitters prepared by the new technique of double beam matrix assisted pulsed laser evaporation (DB-MAPLE). Polymer poly(methyl methacrylate) (PMMA) host was evaporated on a silicon substrate using a 1064-nm pulsed laser beam using a target made of frozen (to the temperature of liquid nitrogen) solution of PMMA in chlorobenzene. Concurrently, the second 532-nm pulsed beam from the same laser was used to impregnate the polymer host with the inorganic nanoparticulate made of the rare earth upconversion compounds NaYF4: Yb3+, Er3+, NaYF4: Yb3+, Ho3+, and NaYF4: Yb3+, Tm3+. The compounds were initially synthesized using the wet process, baked, and compressed in solid pellet targets. The proposed DB-MAPLE method has the advantage of making highly homogeneous nanocomposite films with precise control of the doping rate due to the optimized overlapping of the plumes produced by the ablation of the organic and inorganic target with the infrared and visible

laser beams respectively. X-ray diffraction, electron and atomic force microscopy, and optical fluorescence spectroscopy indicated that the inorganic nanoparticulate preserved its crystalline structure and upconvesion properties (strong emission in green, red, and blue bands upon illumination with 980-nm laser diode) after being transferred from the target in the polymer nanocomposite film. The produced films can be used in applications varying from the efficiency enhancement of the photovoltaic cells, optical sensors and biomarkers to anti-counterfeit labels.

9200-11, Session 2

Self-pulsing in a large mode area, end-pumped, double-clad Ytterbium-doped fiber laser

Daniel Toral-Acosta, Univ. Autónoma de Nuevo León (Mexico); Alejandro Martínez-Rios, Ctr. de Investigaciones en Óptica, A.C. (Mexico); Romeo Selvas-Aguilar, Univ. Autónoma de Nuevo León (Mexico)

The characteristics of self-pulsing in a large mode area Yb-doped fiber laser are presented in this report. A 5 m piece of commercial Yb-doped double-clad LMA fiber 20/400 (from NUFERN, model LMA-YDF-20/400) was used in a linear configuration or Fabry-Perot laser cavity formed by reflection at the two fiber ends. As a pump source, a laser diode array (from COHERENT, model FAP800-R-40W-970.0), operating at 976 nm, with maximum power of 40W was used. Additionally, optical elements like lenses and dichroic mirrors were used in order to separate the pump from the laser wavelength. By using a precision cleaver (from Vytran) each fiber end was prepared. The laser operates in a self-pulsing regime either by using one or two perpendicularly cleaved ends as the feedback mirrors; and operates as a high power broadband amplified spontaneous emission source when both ends are angle cleaved. In the pulsed regime, pulses with kW peak power, 800 ns pulse widths and repetition rates in the order of kHz are generated. Strong sweeping in the laser wavelength is observed when the laser is pulsed, while the possible laser wavelengths are determined by the comb-like ASE spectrum generated by the interference between the modes supported by the fiber core.

9200-12, Session 2

Beam shaping for holographic techniques

Alexander V. Laskin, Vadim V. Laskin, AdlOptica Optical Systems GmbH (Germany); Aleksei Ostrun, St. Petersburg National Research University of Information Technologies, Mechanics and Optics (Russian Federation)

Uniform intensity of laser radiation is very important in holographic and interferometry technologies, therefore transformation of typical Gaussian distribution of a TEM00 laser to flat-top (top hat) is an actual technical task, it is solved by applying beam shaping optics. Holography and interferometry have specific requirements to a uniform laser beam, most important of them are flatness of phase front and extended depth of field. There are different refractive and diffractive beam shaping approaches used in laser industrial and scientific applications, but only few of them are capable to fulfil the optimum conditions for beam quality demanding holography and interferometry. We suggest applying refractive field mapping beam shapers piShaper, which operational principle presumes almost lossless transformation of Gaussian to flat-top beam with flatness of output wavefront, conserving of beam consistency, providing collimated low divergent output beam, high transmittance, extended depth of field, negligible wave aberration, and achromatic design provides capability to work with several lasers with different wavelengths simultaneously. This approach is used in SLM-based technologies of Computer Generated Holography, Dot-Matrix mastering of security holograms, holographic data storage, holographic projection, lithography, interferometric recording of Volume Bragg Gratings. High optical quality of resulting flat-top beam allows applying additional optical components to vary beam size and shape, thus adapting an optical system to requirements of a particular application.

This paper will describe design basics of refractive beam shapers and optical layouts of their applying in holographic systems. Examples of real implementations and experimental results will be presented as well.

9200-13, Session 2

Total absorption in a graphene monolayer in the optical regime by critical coupling with a photonic crystal guided resonance

Jessica R. Piper, Shanhui Fan, Stanford Univ. (United States)

As is well-known, graphene has constant absorption in the visible and near infra-red of around 2.3%. in order to realize many high-performance graphene-based optical devices, enhancement of absorption up to 100% is highly desirable. We numerically demonstrate total absorption in graphene in the near-infrared and visible wavelength ranges by means of critical coupling with guided resonances of a photonic crystal slab. In this wavelength range, there is no plasmonic response in undoped graphene, so the critical coupling is entirely controlled by the properties of the photonic crystal resonance. Due to the relative transparency of the graphene, the underlying photonic crystal resonances are minimally perturbed. But when the leakage rate of a mode out of the photonic crystal is equal to the dissipation rate of that mode in the graphene, the input wave is totally absorbed. We discuss the general theory and conditions for absorption enhancement and critical coupling in a thin film, and give design rules for a totally absorbing system. We present examples in the near-infrared and visible, using both a lossless metallic mirror, and a realistic multilayer dielectric mirror.

9200-15, Session 2

Laser calorimetry of nonlinear-optical crystals based on piezoelectric resonance spectroscopy

Aleksey V. Konyashkin, Oleg A. Ryabushkin, Ivan S. Ulyanov, Moscow Institute of Physics and Technology (Russian Federation) and NTO "IRE-Polus" (Russian Federation)

Conventional method for the precise determination of optical absorption coefficients of nonlinear-optical crystals is laser calorimetry. It is based on measurements of temperature kinetics of air near crystal surface during and after laser irradiation. Both optical absorption and heat transfer coefficients are calculated by solving nonstationary heat conduction equation with Neumann boundary conditions. Novel modification of calorimetry technique that we propose is to use concept of crystal equivalent temperature (?eq) for measuring temperature kinetics of nonlinear-optical crystal interacting with laser radiation. Piezoelectric effect can be used for simple and noncontact way of exciting acoustic vibrations in nonlinear-optical crystals. Piezoelectric resonances are observed in radiofrequency spectra of the crystal response to the applied probe electric field. Calibration of resonance frequency dependence on temperature is performed during crystal uniform heating. This dependence is linear. Nonlinear-optical crystal equivalent temperature kinetics can be measured during its laser heating and subsequent cooling. The ?eq kinetics is directly measured using resonance frequency shift dependence on time. Exponential fitting of experimental results reveal that both heating and cooling events give almost equal values of characteristic kinetic times. This is the main criteria for validity of equivalent temperature concept because in case of cooling the equivalent temperature is identical to the crystal thermodynamic temperature due to high value of its thermal conductivity. Both heat transfer and optical absorption coefficients can be determined using nonstationary heat conduction equation with crystal temperature replaced by its equivalent temperature. Experiments were performed with several crystals using radiation of fiber lasers and its harmonics.

9200-17, Session 2

Design and analysis of large mode area microstructured polymer optical fibre with single mode operation

Than Singh Saini, Vinita Dahiya, Ajeet Kumar, Ravindra K. Sinha, Delhi Technological Univ. (India)

Now-a-days, microstructured optical fibers (MOFs) have gained the attention of many researchers for the development of various new optical devices. The microstructured polymer optical fibers (mPOFs) offer several advantages such as lower melting temperature, more flexible hole patterns, easier manipulation and improved biocompatibility as compared to their silica-based counterparts. Biocompatibility is the key issue for developing mPOF biosensors, because it allows the use of simple immobilization procedures. In this paper, we report a new design of large mode area (LMA) mPOF and analysed its propagation characteristics using finite element method. The structure is characterized by the air holes arranged in hexagonal lattice pattern in the Polymethylmethacrylate (PMMA) polymer. Some of the central air holes have been removed to construct the core. We have optimized the structural parameters (i.e. diameter of air holes'd', center to center distance of air holes '?') for single mode operation of proposed mPOF. The proposed structure offer nominal leakage loss for fundamental mode and very high leakage loss for higher order modes. The single mode operation of the proposed LMA design has been insured by introducing very high differential leakage loss (~10^3) between fundamental and first higher order mode while keeping the loss of leakage loss of fundamental mode very small. At 632.8 nm wavelength, the proposed mPOF of 1.65 m length is able to ensure single moded operation having large mode area of 895 um^2. The proposed design is suitable for high power delivery devices and sensing applications.

9200-18, Session 2

Study of characteristics of MMI devices using matrix approach

Rajib Chakraborty, Saikat Majumder, Univ. of Calcutta (India)

Multimode Interference (MMI) devices, based on the self-imaging theory [1], can reproduce single or multiple image of the input light at periodic distances along its propagation length. They can thus be used to form compact integrated optical circuits having additional advantages of ease of fabrication and large fabrication tolerance. Analyses of such devices using numerical simulation methods are tedious and time-consuming. In this work, the Effective-index-based Matrix Method (EIMM), a computationally fast semi-analytical technique is proposed to study the characteristics of such a device. A 5μm step index waveguide having core r.i. of 1.5 and a cladding r.i. of 1.4 working at 1μm wavelength is considered for the analysis. Using the proposed approach, it has been found that the waveguide supports five modes and the propagation constant of each such mode is determined. The modal profile of each mode can be plotted using EIMM. The total intensity profile due to the combination of all the modes is calculated at the input of the MMI waveguide. The beat-length ($L\pi$) is calculated as in [1], and the image of the input is reproduced at thrice the beat length as is expected. Multiple images are also obtained periodically at intermediate positions. For studying a singlemode-multimode-singlemode structure, the coupling of light from single mode to multimode structure is calculated using the overlap integral factor as in [2].

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9200-56, Session 2

Widely tunable spectrum LED grown on nanostructured substrate

Shizhuo Yin, Chao Wang, Jimmy Yao, The Pennsylvania State Univ. (United States); Claire Luo, The Pennsylvania State Univ. (United States) and General Opto Solutions, LLC (United States); Jun Zhou, Xiaoyan Lin, Shanghai Institute of Technology (China)

A new type of LED-widely tunable spectrum LED is reported in this talk. It is found out that the emitting spectrum of LED can be largely tuned by growing LED on nanostructured substrate. Depending on the type and configuration of the structure, one can achieve both the shorter wavelength (blue) shift and longer wavelength (red shift). A wide tuning range from 420 nm – 510 nm was experimentally achieved. To the best knowledge of authors, this is the widest tuning range reported so far, which will be very beneficial for general LED lighting.

9200-19, Session 3

Digital holographic microscope equipped with volume holographic optical element *(Invited Paper)*

Yeh-Wei Yu, Ching-Cherng Sun, National Central Univ. (Taiwan)

Many advantages of digital holographic microscope have been reported. For example, it is able to apply digital focusing, lens-less imaging and phase image. When we intend to construct a compact digital holographic microscope with high image resolution, there is a trade-off between image distance and image resolution. In this paper, a volume holographic optical element is proposed to solve the problem. The volume holographic optical element is recorded by a side-input plane wave and a normal-output spherical wave. It is possible to produce high-NA spherical reference beam by this setup. Based on the proposed setup, high image resolution and short image distance can be achieved in the same time. Theoretical simulations are used to analysis the proposed idea. Finally, an experimental result demonstrates the proposed idea.

9200-20, Session 3

Application of quantum dots in solid state lighting

Shu-Ru Chung, National Formosa Univ. (Taiwan); Kuan-Wen Wang, National Central University (Taiwan); Yi-Hsuan Yu, National Formosa Univ. (Taiwan)

Semiconductor quantum dots (QDs) prepared by pyrolysis of organometallic compounds are of great interests because of their narrow emission, color tunability, high photoluminescence efficiency (PLE), and size quantization effect. Moreover, because of the narrow emission band of QDs together with the positioning of the peak emission wavelength within the visual spectra band, they offer great potential as they enable optimization of the photometric and colorimetric properties of the device for white light-emitting diodes (LEDs).

However, using binary QDs generally does not result in a high PLE. To enhance the stability and quantum efficiency of the QDs, a core/shell and alloyed material system are preferred. Moreover, in order to make better use of the QDs in light-emitting devices, they are usually required to be stabilized in an appropriate matrix with retention of their initial PLE.

In this study, ternary alloyed QDs with monochromatic light are blended with conventional phosphors. Besides, those monochromatic lights of QDs are also mixed together and then packaged with different types. On the other hand, white light CdSe QD are used alone to fabricate white LED. We have demonstrated that the color rendering index (CRI) and luminous efficiency can be improved by blending conventional phosphors with QDs. The QDs incorporated with yellow or green/red phosphors

have higher PL efficiency. Furthermore, the device performance and optical properties of conventional and white light QDs are compared. QDs with different emission wavelength are blended each other. The result reveals that mixing ratios and PL efficiency between different colors of QDs are important factors. When white CdSe QD is excited by UV-LED without mixing multi-colors of phosphor, high CRI can be obtained for CdSe-based white LED.

9200-21, Session 3

Numerical analysis for a solid-core photonic crystal fiber with tunable zero dispersion wavelengths

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Here we propose a simple design for a solid-core photonic crystal fiber of silica keeping the golden ratio parameter (1.618) between pitch ratio to ratio of air hole diameter ? /d in a subset of six rings of air-holes with hexagonal arrangement. In this way, we propose varying the pitch in the range of 1 ?m to 2 ?m and calculating the diameter of air-holes such that the golden ratio parameter is obtained. In the case when we have a pitch equal to one micron (?=1 ?m), we need air-holes diameters d=0.618 ?m in order to obtain the golden ratio parameter (?/d=1.618), and despite two zero dispersion wavelength (ZDW) points at 725 nm and 1055 nm, this gives us the possibility to use this fiber in supercontinuum generation using a laser emission close to that points. In this research we analyzed a series of fibers using this relation and showed the possibilities of tunable ZDW in a wide range of wavelengths from 725 nm to 2000 nm with low losses and small effective area. In agreement with the ZDW point needed, the geometry of the structure can be modified to the point of having only three rings of air holes that surround the solid core with low losses and good confinement mode. The design proposed here is analyzed and solved using the finite element method (FEM) with perfect match layers (PML), including the material dispersion directly in the model applying the Sellmeier's equation.

9200-22, Session 3

Optical model of reflection grating in collinear holographic storage system

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Collinear holographic storage system is known for simplicity and stability. Due to the reflection structure of collinear system, both reflection grating and transmission grating exist inside the recording disk. The optical behaviors of these two kinds of grating are exactly different. However, only the optical model of transmission grating has been discussed by literatures. In this paper, we propose the optical model of reflection grating of collinear holographic storage system. The paraxial analytic solution is derived out based on VOHIL theorem and Fresnel diffraction approximation. By the analytic solution, we are able to analyze both point spread function and wavelength selectivity of the reflection grating. Accordingly, we find the point spread function for both reflection grating and transmission grating are the same, but the wavelength selectivity of reflection grating are higher than transmission grating. The analysis result benefits the development of collinear holographic storage system.

9200-23, Session 3

Three-dimensional display based on volume holographic kinoform in photopolymer *(Invited Paper)*

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Holographic three-dimensional (3D) display is a promising technique since it can present a 3D scene with all characteristics of real-world objects. Volume holography provides big data capacity and rapid erasure for dynamic 3D display. It has the advantages of good wavelength and angular multiplexing over planar holography because of the Bragg condition. It is expected to carry out dynamic 3D display by recording holographic kinoforms into a volume holographic polymer. The pure-phase wave-front information of a 3D object is calculated by using the computer-generated method to describe the full parallax of the 3D object. The optical system for volume holographic kinoform is designed based on the computational method. A phase-only spatial light modulator (P-SLM) is utilized to modulate the object beam with the hogel information. The phase-modulated data page is recorded in the volume holographic photopolymer. The 3D object can be reconstructed at a designed distance behind the volume holographic polymer illuminated by only reference beam. Volume holographic kinoform can realize dynamic 3D display without any lens or glasses by improving the space-bandwidth product of the display system. This work paves a new way for practical holographic 3D display or the versatile imaging devices based on the high-density volume holographic data storage.

9200-24, Session 3

Effective design of fiber optic polarimetric sensors and its application for structural health monitoring

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Online structural health monitoring (SHM) provides updated information about the health of different engineering structures in real time. Fiber Optic Polarimetric Sensor (FOPS) is one of the SHM techniques which facilitate us with online structural health monitoring (SHM). Both static and dynamic tests with FOPS give excellent results in the field of global health monitoring, but local health monitoring and remote SHM could not be achieved with this method. This is because of the fact that the whole fiber is sensitive and picks up unwanted signals from its surroundings. In the current work, a new design of FOPS has been applied for SHM. It has been shown that in this new design, only the central part of FOPS is sensitive keeping the "leading-in" and "leading-out" parts insensitive, allowing SHM using FOPS that is sensitive only to the region of interest. With this design of FOPS, we get a very stable and accurate signal even at very long distances, making long distance monitoring possible.

9200-25, Session 3

Photonic crystal based nano-displacement sensor

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Till now, various designs on nano-displacement sensors have been proposed. In this paper, horizontal as well as vertical nano-displacement sensor on photonic crystal (PhC) has been proposed. The design for nano-displacement sensor consists of 2D hexagonal arrangement of air holes in silicon (Si) with the radius of air holes, r = 0.4a, where, lattice

constant a = 508nm. The design consists of two identical photonic crystal segments, in which one of the segments is kept fixed and another one is moving with respect to the fixed one. The moving segment has been displaced horizontally as well as vertically with respect to the fixed PhC segment.

It has been found out that the design is highly sensitive with sensitivity 0.00461nm-1 in the displacement region 40nm–120nm for horizontal displacement of the moving PhC waveguide. Similarly, for vertical displacement of the moving PhC waveguide the design is highly sensitive with sensitivity 0.00647nm-1 for zero horizontal displacement in the region 130nm-200nm, 0.00523 nm-1 for 10nm horizontal displacement in the region130nm-200nm, 0.00516 nm-1 for 20nm horizontal displacement in the region 200nm-250nm, 0.00461 nm-1 for 30nm horizontal displacement in the region 130nm-200nm and 0.00466 nm-1 for 40nm horizontal displacement in the region100nm-130nm. From the results, it has been concluded that the proposed design behaves as a Nano-displacement sensor for both horizontal displacement as well as for vertical displacement of the moving PhC waveguide segment at a wavelength of 1550nm.

9200-26, Session 3

Fiber Bragg grating based humidity sensor with wide linear dynamic range

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All-optical temperature insensitive RH sensor is developed employing etched and unetched FBG. Etched FBG acted as RH sensor whereas unetched FBG acted as temperature sensor. Cladding of fiber in FBG region for RH sensor was etched to a few micron levels through controlled etching processes. To investigate sensor characteristics, fiber carrying both FBGs and commercial sensor were carefully fixed inside humidity chamber. Sensors were exposed to repeat step cycles of increasing and decreasing humidity variations at constant temperature (19.8ºC). Completely reversible, highly repeatable response over dynamic range ~ 3% – 94% RH with good sensitivity of ~ 0.0825 pm/%RH is observed.

9200-27, Session 4

2-10 µm supercontinuum broadening using a highly nonlinear chalcogenide microfiber for mid-IR applications *(Invited Paper)*

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Broadband coherent light sources are needed for the mid-infrared (IR) applications like optical coherence tomography, broadband spectroscopy and sensing. Supercontinuum (SC) sources are a novel type of light source that provide a combination of desirable features: high output energy, broadband and flat spectrum, and a high degree of coherence.

Designing highly nonlinear (HNL)-microfiber for the mid-IR region using a conventional fiber structure is difficult: therefore, we propose a new design of fiber structure in which the dimensions of the air holes of the five rings are scaled down from d5 to d1 to shape the dispersion characteristics. Several simulations are performed and optimized fiber geometrical parameters are: pitch ?= 0.8 µm and five different air filling ratios varying from 0.4 to 0.95. The nonlinear coefficient of the designed microfiber is high because of the actions of small dimensions of the air hole arrays along the optical fiber. The proposed fiber is fabricated by As2Se3 based chalcogenide glass. Using full vectorial finite element method (FEM), we calculate the properties of the designed microfiber namely the effective index, the chromatic dispersion, the confinement loss, and the nonlinear coefficient.

The optimized design of the As2Se3 microfiber has an all normal dispersion with flat top equal to -2.3 [ps/(nm.km)], confinement loss less than 10-2 dB/km and a large nonlinear coefficient equal to 7250 (w. km)-1. We optimize the extent of the supercontinuum bandwidth as a function of the input power, fiber length, and pulse width. We investigate the coherence of the generated spectra. Using the generalized nonlinear Schrödinger equation, we generate a large spectral extent in the mid-infrared region from 2650 to 9750 nm by pumping the fiber at ?p=5.24 µm with a femtosecond laser having 50 fs width with a relatively low energy of E=80 pJ in only 2 mm fiber length. The generated SC demonstrates perfect coherence property over the entire bandwidth.

9200-28, Session 4

Mid-infrared supercontinuum generation in chalcogenide step-index fibers pumped at 2.9 and 4.5µm

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The Mid-InfraRed (MIR) spectral range (2-12µm) contains the spectral fingerprint of many organic molecules, which can be probed nondestructively for e.g. detection of skin cancer. For this SuperContinuum (SC) laser sources are good candidates since they can have broadband bandwidths together with high spectral densities. Here we consider a MIR SC laser sources based on chalcogenide step-index fibers with exceptionally high numerical aperture of ~1 pumped either with Er:ZBLAN and Pr:CHALC fiber laser operating at 2.9 and 4.5µm, respectively, having P0=1kW, T0=50ps, ?_R=4MHz and Pavg=200mW.

The optical properties of fibers (dispersion, nonlinearity and confinement loss) are modeled using the finite element tools based on measured refractive indices of the core and the cladding chalcogenide compositions.

Generation of MIR SC is investigated using the Generalized Nonlinear Schrödinger Equation using actual measured fiber loss obtained using FTIR spectrometry. Pumping the fiber at 2.9µm and 4.5µm yields a SC spanning the 3-10 and 3-12.5µm range with around 10 and 20mW converted into the 8-10µm band, respectively.

Using specially designed CHALC SIF in conjunction with pulsed MIR fiber lasers at 2.9 and 4.5µm it is thus possible to generate a MIR SC spanning almost the entire spectral region of interest with ample power being converted into the MIR.

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9200-29, Session 4

Mid-IR supercontinuum generation and applications: a review

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In this paper, the mid-IR supercontinuum generation (SCG) and its applications are presented. First, mid-IR supercontinnum radiation, covering the 3-5 micron spectral range, was successfully realized by launching femtosecond laser pulses centered at 4 microns into IR single

crystal fibers grown by LHPG method. Second, the applications of this unique supercontinuum source such as IR LADAR was addressed.

9200-30, Session 4

Enhanced gain in guest-host liquid crystal photorefractive hybrids

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Photorefractive (PR) hybrid liquid crystal (LC) cells have combined the space-charge field generated in either a polymer (using e.g. C60) or crystalline material (using e.g. Fe2+/Fe3+) with the large birefringence from a LC layer [1,2]. The efficiency of PR beam coupling in hybrid devices is dependent on the amplitude of the interaction of the space-charge field, as well as the ability of the LC molecules to align with the corresponding direction of the field. A guest-host system is comprised of the original (host) LC used in the hybrid cell, doped with a small concentration of an additional material (guest) enabling the LC layer to be more field sensitive, while maintaining the birefringent properties of the host. In this paper, it is shown that when a guest-host LC system is used, a larger PR gain is measured. The PR gain has been measured at several grating spacings and was compared to the gain of the pure LC hybrid system.

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9200-31, Session 4

The calculation of the coherence time of spectral supercontinuum at the output of the fused silica with different parameters of the initial pulse

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In this paper, the dependence of the coherence time of a femtosecond spectral supercontinuum from different initial pulse parameters - wavelength, peak intensity and duration are investigated. It is shown that in the case of generation of femtosecond spectral supercontinuum in silica fiber in the areas of normal, abnormal and zero group velocity dispersion, with an increase of the central wavelength of the femtosecond laser pulse at the input, the coherence time of the radiation with ultra-wide spectrum is significantly reduced. However, in the region of zero group dispersion of fused silica there is a "leap" of the coherence time. There is a "leap" of increasing the coherence time for different initial pulse durations and peak intensity I = 1012 W/cm2 in the zero group velocity dispersion of the optical medium as for the peak intensity I = 1013 W/cm2. It is demonstrated that the value of the coherence time in the zero group velocity dispersion of the optical medium is comparable with the value of the coherence time in the normal group velocity dispersion. In addition, it is shown that with increasing of the duration of the initial pulse width of the peak of the "leap" in the coherence time zero group velocity dispersion of the optical medium decreases. The value of the coherence time is halved with increasing of the initial pulse peak intensity for the same duration by single-order difference.

9200-32, Session 4

Field induced dynamic optical waveguide switches

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In this paper, a new type of optical waveguide switch-field induced dynamic optical waveguide switch is presented. The switching function is realized by electric-field induced dynamic optical waveguide. By applying electric field at different locations, different waveguide paths are created, which result in different output locations. The major advantages of this unique optical switch are broad bandwidth, covering the entire 1300 nm – 1600 nm fiber optic communication window, and ultrafast switching speed (on the order of nanosecond), which can be very useful for next generation reconfigurable optical networks.

9200-33, Session 4

Crystalline deposition of bi-alkali photocathode through molecular beam epitaxy for fast-timing photodetectors

Junqi Xie, Argonne National Lab. (United States)

The next generation fast-timing photodetectors require the development of high-performance photocathodes. In this talk photocathode growth through molecular beam epitaxy is introduced as a promising technique to obtain robust, highly efficient alkali-antimonide based photocathodes. Recent research shows that the quantum efficiency of photocathodes can be significantly enhanced through control of the photocathode crystallinity. Molecular beam epitaxy allows for cost-effective growth of large-area photocathodes with excellent control of the stoichiometry and crystallinity, making photocathodes with exceeding quantum efficiencies and excellent performance. On-going research on the crystalline deposition of alkali-antimonide based photocathodes will be presented, the photocathode composition, crystallinity and performance will also be presented and discussed.

9200-34, Session 4

Phase-shifting holography using Bragg and non-Bragg orders in photorefractive lithium niobate

Ujitha A. Abeywickrema, Partha P. Banerjee, Univ. of Dayton (United States)

The refractive index (RI) of a material can be changed due to several effects such as the optical Kerr effect and the photorefractive (PR) effect. The use of PR materials for implementing real time phase shifting holographic interferometry is discussed in this work. Holographic interferometry (HI) is an effective and rich method for measuring very small (order of a wavelength) displacements and it is widely used for non-destructive testing. Bragg and non-Bragg orders can be generated during two-beam coupling in a PR material due to the induced RI in the material and can be used to retrieve the phase information of the object, as well as the deformation of the object. In previous work, we have shown how object deformation can be determined from monitoring a Bragg order. Furthermore, we have reported on preliminary experiments for determining the depth profile of an object and provided approximate analytic solutions for the Bragg and non-Bragg orders for the case of interacting plane waves. In this work we numerically calculate the exact solutions for the intensities of the Bragg and non-Bragg (higher orders) orders for the case of two incident plane waves, as well as for the case when one of the incident fields is a profiled or image bearing beam. We show how the information from the diffracted order intensities can be

used to determine the amplitude and phase of the 3D object. Similarities with phase shifting holography will be discussed. Numerical results are compared with experimental results performed using lithium niobate as the photorefractive recording material.

9200-57, Session 4

Single-platform Si photonic components for mid-infrared sensing and chemical imaging

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Basic challenges for mid-infrared (MIR) Si photonics are developing of appropriate sources and detectors, detection sensitivity, size minimization and downscaling to a single-platform, spectral tunability. We address such challenges via proper design, modeling and material choice for a series of photonic structures. Our research is done in three steps: modeling, fabrication, characterization. The modeling starts with ellipsometry investigation of Si, Si3N4 and SiOx, to estimate the materials' complex dielectric function in MIR. The technique showed Si and SiN optical transparency in the range ?=4.5-6.5 ?m, and negligible absorption for SiOx, which makes it appropriate for MIR photonics (Fig. 1).

Fig. 2 demonstrates the device concept: MIR source emits electromagnetic field, which is coupled to/from a Si-waveguide (WG) via grating couplers. The WG performs as interaction medium between the propagating field and fluid atop the WG. It results in field attenuation, measured at the output, due to partial absorption by the fluid.

To achieve efficient device performance, size, spectral tuning and evaluation of the attenuation, the structures were investigated by means of 3D photonic simulations.

The structures were fabricated via the 200-mm-wafer-CMOS technology in Infineon involving deep-UV lithography and Bosch etching. PhC structures were fabricated as holes in a Si-slab with SiOx-filling to avoid residuals from the fluid into the holes, which modifies the photonic band gap and device sensitivity.

Figure 3 shows SEM images of the structures. Our paper discusses the design, material characterization, single-platform integration of the source, WG and detector and first experiments with recently fabricated prototypes.

9200-14, Session PMon

Recent advance in application of acousto-optic tunable filters

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This paper aims to inform those interested in the scientific work of a large group of scientists: workers of the Department of Electronics and Optical communications of St. Petersburg State University of Aerospace Instrumentation in collaboration with workers of the Department of Quantum Electronics of St. Petersburg State Technical University in the area of researches and development of acousto-optic tunable filters (AOTF).

Paper discusses the important features of the AOTF structure and their parameters that affect its work, such as: spectral range of optical radiation, spectral resolution, active aperture of the optical radiation, optical transmission of the working spectral range, optical radiation polarization (linear, circular or arbitrary) , diffraction efficiency, contrast, distortion of the optical radiation's front, frequency range of elastic waves, switching time, maximum electric control power, impedance.

Also the AOTF using is considered: AOTF's implications for control of laser radiation, AOTF's application to determine the counterfeit money.

The last part of the report focuses on materials that act as antireflection thin films. Spectral characteristics of "clean" and enlightened substrates of ZnSe and Ge are shown.

As seen from the examples in the report, antireflection thin films increase transmittance of optical elements.

9200-16, Session PMon

Design of equiangular spiral photonic crystal fiber for supercontinuum generation at 1550 nm

Than Singh Saini, Delhi Technological Univ. (India); Amira Baili, Univ. of Carthage (Tunisia); Vinita Dahiya, Ajeet Kumar, Delhi Technological Univ. (India); Rim Cherif, Mourad Zghal, Univ. of Carthage (Tunisia); Ravindra K. Sinha, Delhi Technological Univ. (India)

Photonic crystal fiber (PCF) or holy fiber (HF) is one the most important applications of photonic crystal. PCF are fascinating due to their various novel linear and nonlinear properties. Supercontinuum generation (SCG) in photonic crystal fibers have attracted much attention in different fields such as frequency metrology, multi-wavelength optical sources, optical coherence tomography and pulse compression etc. In this paper, an equiangular spiral (ES) photonic crystal fiber (PCF) in tellurite glass has been designed for nonlinear applications. The proposed ES PCF offer zero dispersion wavelength at 1570 nm. The dispersion properties of the proposed fiber have been analysed using a full vectorial finite element method. Nonlinear Schrödinger equation has been solved using split step Fourier method for generating the supercontinuum. The proposed structure has high nonlinearity (? = 2000 w-1 km-1) at 1550 nm wavelength with very low and flat dispersion -0.152 ps/(nm.km) at 1550 nm. We have generated a bandwidth extent from 900 - 2450 nm in only 2 mm length of tellurite ES PCF with low input pulse energy of 200 pJ by pumping at 1550 nm. The proposed ES PCF design can be a good candidate for nonlinear applications.

9200-35, Session PMon

Self-tuning acousto-optic deflectors with acoustic line made of NaBi(MoO4)2 crystal

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Acousto-optic deflectors are used in variety of optical systems and laser radiation controlling systems. These systems allow real-time optical signals' direction controlling and high-speed laser beam scanning.

There is one unsolved problem of deflector's operation in Bragg diffraction mode, and this problem is preserving diffraction mode or acoustic line's crystal position preserving despite external influences.

In this work many different possible options of feedback implementation are considered. These different possible options allow to preserve deflectors position by piezoelectric rotators. Using of piezoelectric rotators significantly simplifies mechanic scheme of self-tuning deflectors and piezoelectric rotators are much more inertialess than mechanical movers. Of course, one of the main criteria of such self-rotating systems work is the initial setting the deflectors in Bragg diffraction mode.

In additional, new material of acoustic line crystal was investigated as well; it is sodium bismuthate's double molybdate, grown by new technology – low thermal gradient method. As it turned, this crystal has a number of differences from the sodium bismuthate's double molybdate,

grown by traditional Czochralski process, which makes it preferable for use in acousto-optical devices.

9200-36, Session PMon

Enhanced stability of Bi-doped Ge2Sb2Te5 amorphous films

Natalia Korobova, National Research Univ. of Electronic Technology (Russian Federation); Sanjar Dusembayev, Oleg Y. Prikhodko, Al-Farabi Kazakh National Univ. (Kazakhstan); Sergey P. Timoshenkov, National Research Univ. of Electronic Technology (Russian Federation); Konstantin D. Tsendin, Ioffe Physico-Technical Institute (Russian Federation)

Although, several reviews have appeared on various physical properties and applications of chalcogenide glasses, there is no thorough study of local atomic structure and its modification for eutectic Ge-Sb-Te alloys doped with Bi. Ge2Sb2Te5 pure and Bi-doped films were deposited by ion-plasma sputtering method of synthesized GTS material on Si (100) and glass substrates coated with a conductive Au layer which was used as a bottom electrode. The composition of thin-film samples was measured using an electron probe micro-analyzer (EPMA). A qualitative EPMA analysis was used to identify the elemental composition. Variations of the phase composition in as-deposited samples were identified using Raman spectroscopy. Characterization of the basic parameters such as material density, average atomic volume, average coordination number, number of constrains and heat of atomization in dependence on composition, was also given. These parameters were well-correlated with topological and chemical ordered network models. Current–voltage characteristics of different points of the same samples have been measured. Random distribution of inclusions within the sample made it possible to investigate the dependence of switching and memory effects on the phase composition at a constant value of other parameters. Measurements in the current controlled mode clearly showed that the memory state formation voltage does not depend on current in a wide range. Results indicate that the development of imaging technologies phase memory cells need to pay special attention to the conditions of Ge-Sb-Te film preparation. To increase the number of cycles "write – erase" should be additional prolonged annealing of the synthesized films.

9200-37, Session PMon

Error angle determination of the star sensor with liquid cooling

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The paper describes the design studies method of the thermal stability of star sensor with liquid cooling using modern CAD. This technique can be applied to any type of stellar structure devices with the same cooling method. Optimal operation of two circuits for liquid cooling structure of the star sensor has been chosen, using a mathematical model for calculating the coefficient of convective heat transfer. Study defined the angular displacement of the star sensor with liquid cooling (~ 0.3 arc seconds), which is acceptable for star sensors with an accuracy of about 1 arc seconds.

At this level of scientific investigation the developed three-dimensional model of the star sensor assembly comprising a thermally stabilizing ground test equipment allows to determine the angular error due to the temperature loads and optimal parameters liquid of cooling system (for example, the flow rate of fluid , geometrical parameters of cooling circuits , etc.). In the future, this model should be improved, which will consider the impact of other factors (e.g. gravity, vibration, etc.) on the performance of the star sensor.

9200-38, Session PMon

Theoretical for astigmatism Fourier transform-based imaging processor

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We propose a new step imaging method for ladar echo data, which is mainly used in optical imaging processing system of synthetic-aperture imaging ladar. The expression with separated variables is obtained for equation of original echo data for synthetic- aperture imaging ladar. The time-domain data is translated into spatial coordinate expression suitable for space optical conversion. A parallel confocal imaging step is realized by two-dimensional fast Fourier transform of azimuth echo signal after quadratic phase compensation. The Fourier transform is realized by astigmatism principle. It can simultaneously achieve radar goals focusing both on distance and azimuth. Processor scale is effectively reduced. The process of target echo confocal imaging data is simplified. The requirements of ladar imaging processing system are reduced. It has a great advantage in the synthetic-aperture imaging ladar target echo confocal imaging data processing.

9200-39, Session PMon

Quasiperiodic Bragg reflection waveguides

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The Bragg reflection waveguide which have up to date been investigated are usually formed by two identical or different Bragg reflectors which are separated by a low index guiding layer. Some significant effects have been obtained in the BRW with periodic mirrors, particularly: i) the each guided mode has two cutoff points as a result waveguide can be designed to support only the higher-order modes; ii) the possibility of losing a specific mode due to shrinking of the forbidden bandgap into point; iii) the appearance of modes with minus mode order m with using a thin guiding layer; iv) the high dispersion in such waveguides generates slow light in the vicinity of the PBG edges.

At the same time the nonperiodic design of layered reflectors, quasiperiodic or fractal arrangements of their constituents, gives an additional degree of freedom which allows achieving an enhancement of the optical performance in some specific applications. In the present paper we propose symmetric quasiperiodic Bragg reflection waveguide which consist of a low-index guiding layer sandwiched between two quasiperiodic layered mirrors. Here we assumed that both mirrors made up of stacks of alternating layers which are arranged according Thue-Morse or Kolakoski substitutional rules. The transmission characteristics of the guided modes of the proposed quasiperiodic BRW are detailed studied in this paper. In additional influence of changing of the waveguide parameters on the dispersion characteristics of the guided modes is presented. We suppose that this approach would afford much more flexibility for designing and varying BRW structures.

9200-40, Session PMon

Absorption characteristic and two-center holographic recording in LiNbO3:Ce:Ru crystals

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Doubly-doped LiNbO3 crystals can be used to realize two-center holographic storage, which is designed by K. Buse et al. in 1998. The key point of this technique is that two different dopants are used to provide shallower and deeper centers in LiNbO3 crystals. From 1998, the development of new materials with different dopants has become an important direction for two center recording. LiNbO3:Fe:Ru crystal has been reported to perform two-center recording, the results show that Ru is an effective alternative to Mn in LiNbO3 crystals.

Cerium is also known to be an effective alternative to Fe in LiNbO3 crystal. In this paper, LiNbO3:Ce:Ru crystals are investigated to perform two-center recording for the first time. The absorption spectra examination of LiNbO3:Ce:Ru crystals is performed with different annealing treatment, and the results show that there is an absorption peak around 530nm, which can be reduced by the oxidization treatment, and increased by the reduced treatment. A photochromic effect is observed through UV illumination experiment. Two-center recording are investigated with different sensitizing wavelength. The results show that the highest recording sensitivity and dynamic range can be obtained with 405nm sensitizing. The effect of the sensitizing wavelength on photorefractive performance in LiNbO3:Ce:Ru crystal is discussed.

9200-41, Session PMon

Organic photovoltaic cells of fully conjugated poly[2,6- (4,4-bis(2-ethylhexyl)-4H-cyclopenta[2,1-b;3,4-b]dithiophene)-alt-4,7-(2,1,3-benzothiadiazole)] doped with fullerene

Ming Seng Hsu, Jen Wei Huang, Feng Lin Shyu, Chinese Military Academy (Taiwan)

The fully conjugated poly[2,6-(4,4-bis(2-ethylhexyl)-4H-cyclopenta [2,1-b;3,4-b¢] dithiophene)-alt-4,7-(2,1,3-benzothiadiazole)] (PCPDTBT) was a low energy gap (Eg) organic polymer material with polydispersity index (PDI) 1.3. It's the highest occupied molecular orbital (HOMO) 5.2 eV, the lowest unoccupied molecular orbital (LUMO) 3.75 eV and Eg 1.45 eV. As compared with poly-(3-hexylthiophene) (P3HT), the lower Eg made the more absorption in the near-infrared (NIR) area. Its maximum absorption peak was near 800 nm. The optimal conversion efficiency (?p) of single-layered PCPDTBT:PC61BM organic photovoltaic (OPV) device reached 2.44% when the weight ratio of PCPDTBT:PC61BM was 1:2.5. In this study, we changed weight ratio, layer thickness, and solvent to enhance the optoelectronic properties of OPV devices. Variations the layer thickness were processed and investigated leading to an optimum ?p of 2.62 % for a single layer OPV cell with layer thickness of 150nm. The PCPDTBT molecule packed more order when the solvent evaporated to go slow. However, it did not increase the crystal level of PCPDTBT molecule for enhanced ?p.

9200-42, Session PMon

Thermal Effect of Organic Photovoltaic Cells of Fully Conjugated Poly-(3-hexylthiophene) Doped with Derivatized Fullerene

Jen Wei Huang, Ming Seng Hsu, Chinese Military Academy (Taiwan); Tzu-Chin Lin, National Sun Yat-sen University (United States); Ching Yao Hsu, Cantwell-Sacred Heart of Mary High School (United States)

This study primarily employed poly-(3-hexylthiophene) (P3HT): [6,6]-phenyl C61-butyric acid methyl ester (PC61BM) solvent to produce single-layer organic photovoltaic (OPV) cell of single-layer bulk heterojunction (BHJ). The OPV cell structure is ITO/PEDOT:PSS/ P3HT:PC61BM/LiF/Al. In the process, we examined the optoelectronic properties of producing P3HT:PC61BM single-layer OPV cells in various thicknesses of active layer, temperatures, and times of thermal pre- and post-annealing. The results showed that the maximum conversion efficiency (?p) of single-layer OPV cells increased in crystal level of P3HT molecule from low temperature to high temperature process and effective contact area between active layer and metal cathode of device. Thus the ?p value of cells can reach 4.58% after pre- and post-annealing.

9200-43, Session PMon

DLC thin films influence the thermal dissipation of LED lights

Jen Wei Huang, Ming Seng Hsu, Chinese Military Academy (Taiwan); Ching Yao Hsu, Cantwell-Sacred Heart of Mary High School (United States); Hsiao Fan Hsu, Chinese Military Academy (Taiwan)

Thermal dissipation had an important influence in the quantum effect of light emitting diodes (LED) because it enables transfer the heat from electric device away from the heat to the aluminum plate that can be used for heat removal. In the industrial processing, the quality of the thermal dissipation decides by the gumming technique between the PCB and aluminum plate. In this study, we fabricated a ceramic thin film of diamond like carbon (DLC) by vacuum sputtering, soldered the substrate of LED light to enhance the heat transfer. The dielectric coatings were characterized by several subsequent analyses, especially the measurement of real temperature. The X-Ray diffraction (XRD) diagram analysis reveals those ceramic phases were successfully grown on the individual substrate. The results show DLC thin film coating fabricated by vacuum sputtering has lower sheet resistivity, higher hardness, critical load, and thermal conduction, 3.5 Wm-1K-1 to the purpose. The real temperature showed DLC thin film couldn't transfer heat enough and limited work temperature of LED successfully as compared to aluminum nitride.

9200-44, Session PMon

Optimized design of Yb3+/Er3+-codoped cross-coupled integrated microring resonator arrays

Ramona M. Galatus, Technical Univ. of Cluj Napoca (Romania); Juan A. Valles, Univ. de Zaragoza (Spain)

Integrated devices, with ultracompact structures and multi-functional configuration, that incorporate microring resonators as building block elements have been widely disseminated in recent years. They provide various functions in applications such as optical filtering, multiplexing and de-multiplexing, switching, modulation and sensing applications. The practical devices were implemented using various materials like glass, polymer and silicon. The extent of functions can be further expanded by using gain materials. If gain is incorporated inside the ring, losses (intrinsic absorption, scattering, bend, etc.) can be compensated and filtering and amplifying/oscillating functionality are combined.

In this paper we present the analytic model of the complete scattering response of a highly Yb3+/Er3+-codoped phosphate glass microring resonator array that allows to analyze the amplification of the signal obtained at through and drop ports and the laser oscillation regime, in order to obtain an optimized integrated structure. The model evaluates the intensity rates taking into account the interaction of the optical powers (pump and signal) with the dopant ions through absorption/ emission processes. The required high dopant concentrations enhance nonradiative energy-transfer mechanisms and in our model a microscopic statistical formalism is considered for migration-assisted upconversion. The method assumes a single polarization, monomode, resonant behavior of both pump and signal powers.

The performance of the add-drop filter was investigated based on the signal transfer functions for through and drop ports of the integrated cross-coupled microring resonator array, correlated with gain coefficient and its dependence on pump power, signal power and Yb3+/Er3+ concentration.

9200-45, Session PMon

Characterization of long period fiber grating as load sensing

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We show the sensing of load by means mechanically induced long-period fiber grating (MLPFG) made by applying pressure by means a screw to a pair of grooved plates over single-mode fiber. We used a torquemeter in order to obtain precision in the adjustment screw and thus establish an equilibrium pressure applied to a specific region of the optical fiber to form the long period grating mechanically induced fiber. The increase the torque to screw, the resonance wavelength of MLPFG increases its depth over 16 dB. We use a detector to observe the changes amplitude according to the fiber pressure.

9200-46, Session PMon

Resonant tunneling in 2D-photonic superlattices

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Transmissions and resonant tunneling of two-dimensional (2D) photonic superlattices (PhSLs) are discussed. We consider PhSL composed of two alternating 2D-photonic crystals. The structure is denoted as A/B/A/B……A/B, where photonic crystals A and B act as photonic wells and barriers, respectively. The transmission coefficient is calculated using the Transfer Matrix Method (TMM) in combination with Bloch theorem. The transmission spectra of the PhSLs indicate that the formation of photonic minibands and minigaps inside the wells. The positions and number of the minibands can be artificially tuned by varing the well width. By appropriately choosing the structure parameters, this interesting results can be used to develop new photonic devices.

9200-47, Session PMon

Mechanically induced long period gratings in polarization maintaining photonic crystal fiber with a supercontinuum generation source

Eduardo Huerta-Mascotte, Ruth I. Mata-Chávez, Julian M. Estudillo-Ayala, Ana D. Guzman-Chavez, Martin Cano-Contreras, Mónica Trejo-Durán, Roberto Rojas-Laguna, Everardo Vargas-Rodriguez, Igor V. Guryev, Univ. de Guanajuato (Mexico)

We present the results from the fabrication and characterization of mechanically induced long period fiber gratings in polarization maintaining photonic crystal fiber (PM-PCF). A supercontinuum source in the range of 600nm - 1700nm is used. This source is generated using a micro-chip laser at 1064nm and a single mode fiber. A long period grating of period ?=570?m is induced over 4cm long unjacketed PCF using a V-grooved aluminum plate. . External pressure is gradually applied with a metal screw and a torque meter and a loss dip with ?_r=810nm resonance wavelength is observed. Low insertion losses are depicted from (1-3) dBm with a bandwidth of about 30nm and a loss dip around 15dBm. Sensitivity for this preliminary work is found at 27 dB/Lbf-in. Several applications are potentially possible with the optimization of the transmission spectrum controlled by pressure and make them potential candidates as industrial sensors.

9200-48, Session PMon

Photoconductivity of ZnO based granular structures

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We studied experimentally the granular structures prepared on the base of ZnO thin films. The influence of acceptor or donor complex, caused by oxygen vacancy and interstitial zinc atom, and impurities (Li or Ga) on the crystallite structure conductivity have been investigated. The effect of granule size and crystallite structure on photoconductivity kinetics was studied. The new method for determination of current density in thin conducting film was developed, which allowed to diagnose one dimensional conductivity in ZnO:Ga films. The experimental results are interpreted on the basis of the scaling hypothesis and the percolation theory.

9200-49, Session PMon

Design of the binary-encoded fringe pattern for projected fringe profilometry

Wei-Hung Su, National Sun Yat-Sen Univ. (Taiwan)

An approach using lithography techniques to fabricate a binary-encoded fringe pattern for projected fringe profilometry is described. The sinusoidal fringes are spatially encoded with a stream of binary stripes. Phase unwrapping is then performed based on the transmittance of the binary stripes. The period of the binary stripes can be enlarged by increasing the length of the encoded stream. Its tolerance of phase unwrapping is therefore increased. Advantages of the fringe pattern for phase unwrapping include (1) reliable performance for colorful objects, (2) unwrapped errors only confined in a local area, and (3) low computation cost.

9200-50, Session PMon

Projected fringe profilometry for non-diffusive objects

Wei-Hung Su, National Sun Yat-Sen Univ. (Taiwan)

A full-field method using fringe projection techniques to perform the 3D profile measurement for a non-diffusive object is proposed. It employs a hologram as the fringe projection device. Even though the inspected object is non-diffusive, the proposed method can retrieve the 3D shape precisely.

9200-51, Session PMon

3D shape measurements for plano-convex lenses using fringe projection techniques

Wei-Hung Su, National Sun Yat-Sen Univ. (Taiwan); Chau-Jern Cheng, National Taiwan Normal Univ. (Taiwan)

An algorithm using the fringe projection technique to perform the 3D profile measurement for a plano-convex lens is proposed. A fringe pattern is illuminated onto the lens object, and a CCD camera is employed to record the transmitted fringes on the screen. Fringes on the obtained image are deformed both by the refractive index and the topography of the object, and are analyzable to retrieve the 3D shape.

9200-52, Session PMon

A scanning approach using fringe projection techniques for 3D profile measurements

Wei-Hung Su, National Sun Yat-Sen Univ. (Taiwan); Nai-Jen Cheng, National Kaohsiung Univ. of Applied Sciences (Taiwan)

A scanning approach using fringe projection techniques to perform the 3D shape measurement for a complicated object is proposed. Even though the depth discontinuity on the inspected surface is pretty high, the proposed method can retrieve the 3D shape precisely.

9200-53, Session PMon

Vibrometry analysis of electrooptical coupling near piezoelectric resonance

Robert McIntosh, Amar S. Bhalla, Ruyan Guo, The Univ. of Texas at San Antonio (United States)

This research explores new possibilities of improved electrooptic interaction at high frequencies, as a result of coupled electrooptic effects near selected piezoelectric resonances. Results suggest that the key to a large electrooptic interaction at high frequencies is the gradient of the strain and the acceleration of the accompanying lattice waves in a modulated crystal. While strains tend to be damped, acceleration of the lattice wave retains its amplitude at high frequencies. A laser Doppler vibrometer measurement and numerical FEA modeling (COMSOL) were carried out over a broad range of frequencies, including the fundamental resonant modes and higher order harmonics.

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9200-54, Session PMon

Homodyne and heterodyne optical interferometry for frequency dependent piezoelectric displacement measurement

Keith G. Delahoussaye, Amar S. Bhalla, Ruyan Guo, The Univ. of Texas at San Antonio (United States)

The electromechanical coupling in piezoelectric materials has been widely studied however a unified view of this interaction as function of frequencies using different measurement techniques has not previously been available. This study examines and compares multiple optical based homodyne and heterodyne interferometry techniques for displacement measurement, over a wide range of frequencies, and including a comparison made by using a commercial Laser Doppler Vibrometer. Ferroelectric lead titanate $PbTiO_3$ with high ferroelectric strain is studied in this work. Frequency dependence of the electromechanical displacement is obtained using multiple techniques and the emphasis is given to near resonant frequency interrogations.

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9200-55, Session PMon

Ponderomotive force induced nonlinear interaction between terahertz wave and air plasmas

Chengxun Yuan, Harbin Institute of Technology (China) and The Pennsylvania State Univ. (United States); Shizhuo Yin, The Pennsylvania State Univ. (United States)

In this paper, ponderomotive force induced nonlinear interaction between terahertz wave and air plasmas is presented. It is found out that the dimension of THz wave can be altered by the ponderomotive force induced nonlinear interaction between terahertz wave and air plasmas. The amount of change also depends on the frequency of the Terahertz wave. The higher the frequency, the bigger the amount of change will be. This unique nonlinear interaction can be very useful for controlling, adjusting, and modulating Terahertz wave.

9201-1, Session 1

Holographic Data Storage: Science Fiction or Science Fact? *(Invited Paper)*

Ken E. Anderson, Mark Ayres, Fred Askham, Brad Sissom, Akonia Holographics, LLC (United States)

The realization of a commercial holographic data storage device has remained elusive for many decades. Will it ever become a reality? Why have other efforts failed? Can it still compete with today's storage solutions?

While some believe that holographic data storage will never be commercialized, there are many that understand that there has been a confluence of technology that has come together to make engineering a cost-effective solution not only feasible but merely a matter of packaging. Akonia Holographics is in the process of demonstrating world record bit densities as well as a new holographic architecture that will result in more than a decade of bit density improvements; and while packaging will still be challenging just as it is with any new technology, the answer to the question of whether holographic storage will ever be commercialized is not so much a technological question as much as it is a business and funding issue.

9201-2, Session 1

Data pages recording and reconstruction by dual-channel polarization holography with coherent addition method *(Invited Paper)*

Daisuke Barada, Utsunomiya Univ. (Japan)

Dual-channel polarization holography is an optical recording techniques to simultaneously record two images including a signal beam with two orthogonal polarization states. The two images are simultaneously reconstructed. The reconstructed two images can be optically separated by using a polarizing beam splitter and captured by using two image sensors. In this paper, another method for extracting two images from a reconstructed signal beam using an image sensor is introduced. In the method, two reference beams for extraction are interfered with the reconstructed two signal beam components and an interference pattern is captured using an image sensor. The recorded two images are independently extracted by Fourier transform method.

In this study, two data pages with p- and s-polarization components are simultaneously recorded on a polarization-sensitive medium made of PQ-PMMA by inline and off-axis systems. In inline system, grating patterns are displayed on two spatial light modulators (SLMs), and a recording signal beam including p- and s-polarization components are generated as diffracted beams. Two zero-order beams are used as two reference beams. In reconstruction, a recorded signal beam are reconstructed by illuminating two reconstructing illumination beams. Then, two reconstructed signal beam components and two illumination beams are superposed on a CCD camera and the interference pattern is analyzed by Fourier transform method. In case of off-axis system, other two beams to be interfered with the reconstructed signal beams are illuminated. Then, the reconstructed two data pages are independently extracted by Fourier transform method.

9201-3, Session 1

Formalization and experimental evaluation of cavity-enhanced holographic readout

Bo E. Miller, Yuzuru Takashima, College of Optical Sciences, The Univ. of Arizona (United States)

Archival data storage requires a high data density, low failure rate, and long shelf life. As a result, optical storage such as Blue-Ray and Holographic Data Storage Systems (HDSS) are better suited than pure magnetic and solid state media. Furthermore, HDSS boasts comparable or even higher storage density than multi-layer, bit based, systems and has a comparable anticipated shelf life, so HDSS is one of the choices for archival storage. One of the challenges for HDSS is a very small diffraction efficiency comparable to noise when a large number of pages are multiplexed.

Prior works have reported that diffraction efficiency can be enhanced by recycling the read beam with a planar Fabry-Perot cavity upon readout of hologram. This enhancement inversely scales with the diffraction efficiency of the hologram, so it is well suited to HDSS with a large amount of multiplexing.

We formalized how diffraction efficiency and Bragg Selectivity scale for the cavity-enhanced readout case along with other cavity-enhanced writing and readout. Theory predicts ~200 % of enhancement in diffraction efficiency is feasible when the power loss of the holograms is ~9 %. We have experimentally verified a 50% enhancement of the diffraction efficiency for a hologram written in Fe:LiNbO¬¬3 with a 532 nm wavelength, pulsed, DPSS, Nd-YAG, laser and read by a red He-Ne laser. The Bragg Selectivity under the cavity-enhanced readout is experimentally confirmed, and it agrees with theoretical prediction.

9201-4, Session 1

Digital synthesis, multiplexed recording, and data reconstruction of 1D-Fourier holograms in projection-type optical storage system

Evgeny Y. Zlokazov, National Research Nuclear Univ. MEPhI (Russian Federation); Sergey Odinokov, Bauman Moscow State Technical Univ. (Russian Federation); Nikolay N. Evtikhiev, Rostislav S. Starikov, Vladimir Bobrinev, National Research Nuclear Univ. MEPhI (Russian Federation); Aleksander Betin, Sergey Donchenko, Bauman Moscow State Technical Univ. (Russian Federation)

High-precision optical scheme of the most presented holographic memory systems that is required to achieve challenging information density causes high prices of the recording device. In our previous works we represented the decision of this problem based on encoding a standard holographic memory data pages as computer-generated Fourier holograms (CGFH) that can be represented as grayscale bitmap images and transmit the synthesized holograms onto holographic medium using spatial light modulator (SLM) and simple optical projection scheme with multiple aperture reduction. The synthesis method of CGFH that we used was based on two-dimensional discrete Fourier transform calculation. Further attempts of multiplexed record of synthesized CGFHs on holographic medium showed inability to separately reconstruct the encoded data pages from overlaid microholograms. The decision of this problem was application of computer generated one-dimensional Fourier holograms (1D-CGFH). The object encoded on such a hologram can be reconstructed using anamorphic optical elements such as cylindrical lenses. In this article we represent the basic principles of 1D-CGFH synthesis, an optical setup for encoded data reconstruction from such a holograms, and the results of experimental modeling of 1D-microholograms multiplexed recording on holographic medium.

9201-5, Session 2

FePt heat assisted magnetic recording media: status and roadmap *(Invited Paper)*

Dieter Weller, HGST (United States)

Heat-assisted magnetic recording (HAMR) media requirements and challenges to extend the areal density (AD) beyond recently achieved

1 Tb/in2 [1] will be discussed. The current focus is on granular high anisotropy chemically ordered and well textured L10 FePtX-Y-perpendicular media with an average grain size < D>=8-10nm and sigma_D/D ~ 20% [2]. Reducing < D> down to 3-5 nm and achieving sigma_D/D <10-15% in principal will allow to increase AD by a factor of four [2]. FePtX-Y media with X~ 10at% Cu or Ni reduce the Curie temperature ~100 K below Tc,bulk=750 K thereby lowering the recording energy requirement. Grain-to-grain segregants like Y=C, SiO2, TiO2 etc. are used to exchange decouple grains and to achieve higher perpendicular than in plane thermal conductivity. A key seed layer is fcc MgO(100), which expands the FePt a-parameter and establishes out-of-plane c-axis orientation. Tensile stress facilitates the formation of well oriented L10 FePt grains, which are grown at temperatures of 600-650degC. A c/a lattice parameter ratio close to 0.96 and chemical ordering >90% result in perpendicular magnetic anisotropy Ku~5.10^7 erg/cm^3 [2, 3]. Thermally stable grains down to D~4 nm and 10-12 nm thickness are expected to extend AD toward 4 Tb/in^2 [1, 2].

[1] A. Q. Wu et al., IEEE Trans Mag. 49, 779 (2013); X. Wang et a., IEEE Trans Mag. 49, 686 (2013)

[2] D. Weller et al., pss A, 210, 1245, (2013); D. Weller et al., IEEE Trans Mag 50, 3100108 (2014)

[3] S. Wicht et al., J. Appl. Phys. 114, 063906 (2013)

9201-6, Session 2

Novel characterization methods for HAMR recording *(Invited Paper)*

Michael Alex, Xiao Wu, Alex Chernyshov, Matt Gibbons, Antony Ajan, Western Digital Corp. (United States)

Being a combination of magnetic and thermal recording, characterizing and understanding the heat assisted magnetic recording (HAMR) process presents a number of novel challenges. In this talk, we will review several novel experimental methods used to characterize HAMR heads and media.

9201-7, Session 2

Characterization of HAMR using pulsed laser light *(Invited Paper)*

Kevin R. Heim, Edward C. Gage, Tim Rausch, Seagate Technology LLC (United States); Alfredo S. Chu, Pu-Ling Lu, John W Dykes, Seagate Technology (United States)

Pulsed HAMR recording is being developed to improve HAMR reliability. In conventional HAMR recording systems the laser is on and at a fixed power during the writing of the entire sector. In a pulsed HAMR implementation, the laser is turned on and off during the bit cell. For example, for a 50% duty cycle, the laser is on for half the bit cell and off for the remainder of the bit cell. Unlike traditional HAMR recording where the transitions are formed when the magnetic writer switches, in a pulsed implementation, the transitions are formed during the pulsing of the laser since by design, the magnetic writer switches when the laser is off. In this paper we show spin stand recording performance of pulsed HAMR recording systems and compare the performance to pulsed recording. In particular, we show the importance and sensitivity of having proper alignment between the phase of the optical and magnetic signals and their effect on bit error rate.

9201-8, Session 2

Lubricant Depletion under Various Laser Heating Conditions in Heat Assisted Magnetic Recording (HAMR)

Shaomin Xiong, Haoyu Wu, David B. Bogy, Univ. of California, Berkeley (United States)

Heat assisted magnetic recording (HAMR) is expected to increase the storage areal density to more than 1 Tb/in2 in hard disk drive (HDD). In this system, a laser is used to heat the magnetic media to the Curie point (~400 °C) during the writing process. The lubricant on the top of a magnetic disk could evaporate and be depleted under the laser heating. The change of the lubricant can lead to instability of the flying slider and failure of the head-disk interface (HDI). In this study, a HAMR test stage is introduced. The laser can be focused to the disk surface uniformly in this stage at different power levels. The laser can be synchronized to the spindle encoders and the total radiation time can be controlled precisely using a field programmable gate array (FPGA). The effects of laser heating repetitions, laser power levels and disk linear speed are investigated experimentally. The effect of thickness of the mobile lubricant is also discussed.

9201-9, Session 3

Advances in macromolecular data storage *(Invited Paper)*

Masud Mansuripur, College of Optical Sciences, The Univ. of Arizona (United States)

Many of the traditional problems in disk and tape data storage can be overcome if data-blocks were to be released from the confines of a disk (or tape) and allowed to float freely between read/write stations (i.e., heads) and permanent “parking spots.” The heads and parking spots thus become fixed structures within an integrated chip, while the macromolecular data blocks themselves become the (mobile) storage media. In this scheme, a large number of read/write heads could operate in parallel, the heads and parking spots would be constructed (layer upon layer) in a truly 3-dimensional fashion, and individual nanometer sized molecules - strung together in a flexible macromolecular chain - would be used to represent the 0’s and 1’s of binary information. We discuss the potential advantages of this alternative scheme for secondary data storage and, to demonstrate the feasibility of the concept, present results of experiments based on DNA molecules that travel within micro-fluidic chambers. Since our first proposals to develop macromolecular data storage systems, other groups have contributed to developments in DNA-based techniques for information storage and processing. In this presentation we will discuss the latest developments reported by other groups as well.

9201-10, Session 3

Plasmonic coupling effects for readout of nano recording marks *(Invited Paper)*

Din Ping Tsai, Academia Sinica (Taiwan)

Nano recording marks smaller than the diffraction limit is not a challenge now. Optical readout of nano scale recording marks with low bit-error-rate is the real challenge. Plasmonic near-field optical coupling effects of nano recording marks are investigated. A concept of coupling-unit for each recording mark is introduced and tested. Results show the possibility of ultra-high density optical recording and readout system.

9201-11, Session 3

Sapphire optical discs for long term data storage

Andriy Kryuchyn, Viacheslav V. Petrov, Anatoliy S. Lapchuk, Semen M. Shanoylo, Yevgeniy Morozov, Institute for Information Recording (Ukraine)

Thirty years the polycarbonate optical disk (POD) is successfully used for digital data storage and is the main means of dissemination of information. In view of the significant advances in magnetic recording technology and solid-state memory, which provide significantly larger than the POD data storage density, the role of PODs decreased. The problem of long-term storage is very important in nowadays, however due to the characteristics of materials applied in the POD they could not take this technical niche.

The report proposed and implemented method of long-term data storage on the basis of sapphire optical disc.

It is proved that the application of optical disc based on mono-crystalline sapphire is one of the most promising due to unique physical properties of sapphire – chemical resistance, high temperature melting, and very small sensitivity to radiation. However the sapphire is birefringence medium that creates a serious obstacle in its application for data storage due to astigmatism aberration. The authors proposed and implemented a method to compensate astigmatism aberration which is based on using the mono-crystalline sapphire optical disk with 001 crystal orientations and special optical system that compensates wavefront phase distortions in the sapphire disc.

The data recording on 80 mm sapphire optical disc and reading through the substrate were realized in experiment. The information was recording by the laser master recording station (in CD format). The relief obtained in the photoresist on disk surface was metalized. CD reader with a compensator of astigmatism aberration is used to read the information through sapphire disk. Error test demonstrated high signal quality.

In order to obtain really long-term data storage, structure should be realized as a micro-pattern on sapphire surface with followed high temperature metal coating.

9201-12, Session 3

Multilayer optical data storage medium by nonlinear photobleaching

Cory W. Christenson, Anuj Saini, Case Western Reserve Univ. (United States); Christopher J. Ryan, Jeremiah A. Heilman, Heather M. Lemire, Folio Photonics LLC (United States); Christoph Weder, Univ. of Fribourg (Switzerland); Jie Shan, Kenneth D. Singer, Case Western Reserve Univ. (United States)

Numerous technologies have been proposed to increase the capacity of optical storage media toward the terabyte level, which has failed to keep up with the capacity of magnetic media. Solutions based on organic materials are promising due to their low cost and ease of processing, but are difficult to write with CW lasers. We have reported optical data storage in 23 layers of a 75?m thick periodic bilayer polymeric film using a 405nm CW laser. This film was produced using multilayer polymer co-extrusion, having 300nm writing layers separated by 3?m buffer layers. This allows for films with many closely-spaced writable layers to be produced in large areas low cost, and the nanoscale active layers improves the bit confinement and the axial density, improving the much-needed capacity.

We report here on the investigation of the nonlinear photophysics during writing, which is based on photobleaching of organic fluorophores, such as 1,4-bis(?-cyano-4-octadecyloxystyryl)-2,5-dimethoxy¬benzene (C18-RG). Spots are written by pulsing a 405nm diode laser from 20ns duration and up, using various intensities. We find that both photochemical and thermal effects contribute to the photobleaching, leading to a non-linear bleaching dependence on power. This allows for use of these films for ODS with a CW laser and a one-photon writing process. The effect of different non-fluorescing organic dopant molecules is also explored, which can enhance the thermal effect. We interpret our results using a model of thermally activated molecular transition rates. Results are discussed in terms of the needs for high capacity optical data storage.

9201-13, Session 3

Co-extruded organic films and optical system for multilayer optical data storage

Christopher J. Ryan, Kenneth D. Singer, Cory W. Christenson, Jeremiah A. Heilman, Heather M. Lemire, Folio Photonics LLC (United States)

3D optical data storage significantly improves upon the storage density of its 2D predecessors. However issues arise in the fabrication and use of more complex media. Specifically, there are limits to the scalability of conventional layered media.

To mitigate these issues we utilize polymer co-extrusion to produce multilayer films for use as storage media. This method creates heterogeneously layered periodic structures with dozens of writable layers. These co-extrusion methods are easily scalable to thousands of layers and can work with a wide variety of photopatternable materials.

During fabrication, we create 64 layers of photopatternable polymer separated by 64 layers of transparent, inert polymer. Data is stored by linear absorption of a 405nm diode laser. This results in fluorescence photobleaching with submicron axial spacings. To date, we have reported data storage within 23 layers of this film. Data is not stored through the full volume of the film as the only 23 layers fit within the working distance of our objective lens. Improvements to the optics are expected to significantly increase the number of resolvable layers.

We will report aging and uniformity studies on these films. We will also report on the hardware necessary to address these films. Confocal methods are used, but the commercial need for a dry microscope objective requires corrective optics. An optical model of a telescope with variable tube length to control the spherical aberration is presented, as well as opto-mechanics to find and read the many heterogeneous layers.

9201-14, Session 4

Optical compensation and enhancement techniques for holographic digital data storage system *(Invited Paper)*

Yuzuru Takashima, College of Optical Sciences, The Univ. of Arizona (United States)

Due to the nature of the recording principle, the SNR of Holographic Data Storage System (HDSS) is sensitive to optical and mechanical disturbances such as lens aberrations, mechanical vibrations and change of the environmental temperature during writing and reading out holograms. To solve the problem, thermal control and management of the optical parameters such as tuning of wavelength, and write and read out geometry are inevitable and have been actively investigated. In addition, massive multiplexing of pages requires a large dynamic range for the recording material, thus eventually the high dynamic range material become a bottleneck to design system even higher data capacity.

We challenged the problem by adopting optical compensation and enhancement techniques. First, by identifying the sensitivity of recording geometry, we analyzed how the change of the thermal environment affects signal level. To mitigate the mechanical perturbations, we revisited to a classical theory in holography, a time averaged holography, and found that a post compensation of deterioration of SNR is feasible even it is due to the mechanical disturbance while recording.

Also, we review cavity-based techniques in HDSS which has a potential to optically enhance the dynamic range of the material. Specifically, we address formalization of the cavity-enhanced diffraction efficiency and

Bragg selectivity while addressing feasibility of the technique for HDSS used in a practical field.

9201-15, Session 4

Playback of beyond high definition video signal in holographic data storage system with wavefront compensation and parallel signal processing *(Invited Paper)*

Tetsuhiko Muroi, Nobuhiro Kinoshita, Norihiko Ishii, Koji Kamijo, Hiroshi Kikuchi, NHK Japan Broadcasting Corp. (Japan)

We have developed holographic data storage system that could demonstrate real-time playback of beyond high definition video signal. In this system, to increase the data-transfer rate of the reproduced data, we focused on improvement of the signal-to-noise ratio (SNR) of the reproduced data and signal processing speed. The SNR of the reproduced data strongly affects the signal processing speed. One of the factors that deteriorate SNR is shrinkage in the medium. This shrinkage distorts recorded holograms and degrades the quality of the reproduced data. Then, we have been studying wavefront compensation to improve the SNR of the reproduced data degraded by hologram distortion. We have found that controlling the defocus component of the reference beam is effective to compensate for distortion and improve the SNR. In addition, we have been developing parallel signal processing to increase the data-transfer rate. We used three GPUs in the signal processing unit; one was for the reproduced data detection from the reconstructed image and two for the LDPC decoding for error correction of the reproduced data. The LDPC decoding needed much time comparing with the data detection. Therefore, we made the signal processing in which detected data in the GPU for the data detection were sent to the two GPUs for the LDPC decoding alternatively. We have implemented wavefront compensation for defocus component and developed parallel signal processing with three GPUs for our holographic data storage system. Using this system, we demonstrated real-time playback of the beyond high definition video signal with 50 Mbps.

9201-16, Session 4

Shifting tolerance for multilayer collinear holographic data storage

Jinqiu Liu, Liangcai Cao, Qingsheng He, Guofan Jin, Tsinghua Univ. (China)

Collinear holographic data storage (CHDS) is promising in next-generation high-density optical data storage due to the three-dimensional shifting multiplexing with a high numerical aperture objective, which is based on both the page-oriented volume holographic recording and the multilayer CD/DVD recording technology. Various multiplexing methods, data-coding methods and signal processing methods have been proposed for CHDS [1]. In our previous work, we have proposed the orthogonal-reference-pattern-modulated shift multiplexing method [2, 3]. To make full use of the dynamic range of the recording medium, some practical problems related to the implementation of the multilayer CHDS are still under investigation. The three-dimensional shifting tolerance is a key factor to determine the precision of the actuator. In this work, the influence of the lateral and longitudinal positioning error on the image quality of reconstructed data page is analyzed for the multilayer CHDS. The tolerable positioning error is obtained according to the signal to noise ratios of the reconstructed data pages. The system parameters, such as objective numerical aperture and the recording wavelength, perform different influences on the tolerable positioning error, which are optimized to reach a compromise between the storage density and the system tolerance. A terabyte capacity is demonstrated in our multilayer CHDS system.

9201-17, Session 4

Influence of aberrations on signal-to-noise ratio in microholographic recording

Ryuichi Katayama, Fukuoka Institute of Technology (Japan)

Microholographic recording is promising for realizing next-generation optical data storage systems because of its affinity with conventional optical disk systems. To ensure media exchangeability in the optical data storage systems, it is necessary to clarify the influence of aberrations on a readout signal. The author has previously investigated the influence of aberrations of recording and readout beams on the readout signal level through a numerical simulation. The objective of this paper is to investigate the influence on the signal-to-noise ratio of the readout signal.

The wavelength of the laser was 405 nm and the numerical aperture of the objective lenses was 0.85. For 10^4 kinds of patterns in which 7^3 bits (0: without microhologram, 1: with microhologram) were randomly recorded in the in-plane and vertical directions with 0.3 micron and 1.5 micron intervals, respectively (recording density: 7.4 bit/micron^3), the signal level with non-confocal detection when the center bit was reproduced was calculated using coupled wave theory. One of the spherical, coma, and astigmatic aberrations with the root-mean-square wavefront aberration of 0.07 lambda was added to the readout beam. The signal-to-noise ratio was calculated based on the averages and standard deviations of the signal levels for bits 0 and 1.

The calculated signal-to-noise ratios when the spherical, coma, and astigmatic aberrations were added were 2.6, 2.7, and 2.9, respectively, which means that the above recording density is feasible if we allow the signal-to-noise ratio of 2. It is considered that further improvement in the recording density is possible with confocal detection.

9201-34, Session PMon

Data read-out from the crystalline x-ray optical memory medium protected by thin cover layer

Robert H. Bezirganyan Jr., Hakob P. Bezirganyan, X-ROM, Inc. (United States); Siranush Bezirganyan, Bellevue College (United States)

X-ray optical data storage medium named X-ROM is an ultra-high density hard x-ray optical data carrier with several storage layers and data density of about 10 Tbits per square inch for each storage layer. X-ROM consists of crystalline wafer in which the sub-surface amorphous nanometer-size reflecting speckles (nano-pits) of x-ray high-reflectivity material are generated (recorded). Data read-out procedure is performed via the grazing-angle incidence hard x-ray backscattering diffraction (GIXB) hold inside data carrier. Glancing incidence allows the simultaneous data read-out from large area of X-ROM. We assume that diffracting lattice planes of crystalline wafer are normal to x-rays entrance surface. Read-out device detects data by measuring changes in x-ray beam intensity reflected from the various surface points of data carrier. An especially interesting case occurs when GIXB is realized under the conditions of specular wave suppression mode. One of the conditions for the GIXB realization requires a high level of the smoothness for the primary x-ray beam entrance surface, and, consequently, the protection of surface from various damages. All types of digital information carriers, and especially the novel ultrahigh-density optical data carriers, need a surface protection by covering with a thin polymer layer or another low reflecting material. Thus, the performance of additional investigations is necessary to be aware that mentioned data read-out technique also could be applicable in presence of a cover layer. We consider in presented theoretical paper a specular beam suppression phenomenon in the case of GIXB by single crystal wafer covered with thin non-diffracting layer.

9201-35, Session PMon

Six-dimensional optical storage utilizing wavelength selective, polarization sensitive, and reflectivity graded Bragg reflectors

Shangqing Liu, Willow Optics Corp. (Canada)

A six-dimensional optical storage system has been designed, and its feasibility has been demonstrated by theoretical investigations.

In the system, the semiconductor laser arrays emit multiple beams with different wavelengths, selected polarizations and encoded intensities. During each period, these beams create multiple plane volume gratings around beam focuses overlapped in a small volume in photorefractive and polarization sensitive photopolymer as each storage cell. With two-photon absorption writing, a standard optical drive can create 100 data layers in rotational disk with smaller storage cells since frequency doubling. With optical coherence tomography reading, the stored data are retrieved with low crosstalk noise and high signal-to-noise ratio of over 75 dB.

The design is based on proved physical mechanisms and available optical material, which makes the system actually practicable. The storage cell diameters and lengths are large of ~1?m and ~10?m, which greatly reduce the system complexity since less fine beam focusing and tracking, and make the system compatible with CD and DVD.

The storage cell capacity depends on the value of PI^W, (W, I and P are write beam wavelength, intensity level and polarization direction numbers), so this system can have large capacity and fast data transfer speeds even for moderate W, I and P. When W=76, a DVD sized disk can store over 25 Tbytes with read and write/erase speeds of over 30 Gbits/s and 10 Gbits/s for I=5 and P=9. And even I=2 and P=3, the disk capacity and read speed can still be over 12 Tbytes and 14 Gbits/s.

9201-36, Session PMon

Analysis of near-field method for optical data storage using microstrip probe under illumination and illumination-collection mode

Andriy Kryuchyn, Viacheslav V. Petrov, Anatoliy S. Lapchuk, Yevhenii Morozov, Institute for Information Recording (Ukraine)

The use of near-field method in optical recording can increase informational capacity of optical disc more than an order of magnitude. At the same time, widespread use of scanning near-field optical microscope constrained by its low optical efficiency and high noise level. A number of authors propose a new design of optical probe based on «metal-dielectric-metal» structure, so-called symmetric microstrip line (microstrip probe). Its high optical efficiency has been proved theoretically and fabrication technology of microstrip probe was developed recently.

The report presents the numerical analysis of information reading process from ROM disc using microstrip probe consisting of quartz core and aluminum coat strips. We assumed that the disc surface is covered with a thin gold layer on which rectangular shape pits are situated. The simulation was performed using finite difference time domain method. Simulation was performed at the radiation wavelength of 405 nm. The signal was simulated in illumination and illumination-collection mode.

It is shown that illumination mode provides amplitude modulation depth of signal (contrast) Cff = 0,12 ÷ 0,15. However, due to the interference effects the amplitude of the signal depends on probe length and signal has significant crosstalk due to the excitation of surface plasmon polaritons in the gold layer of the disk.

Significantly higher signal amplitude with higher contrast Cnf = 0,53 ÷ 0,65 was obtained at illumination-collection mode (pure near-field method). The significant changes of the phase of the reflected wave from the end of probe (?? = 14° ÷ 24°) when it pass above the pit allows to obtain high quality phase-contrast signal at this mode. The method using a signal from special calibration flat areas on the disc surface that allows the precise control of the distance between the probe and the disk in the range between 0 and 100 nm is proposed.

9201-37, Session PMon

Storage capacity of collinear holographic storage system improved by lens-array reference modulation

Yeh-Wei Yu, Chih-Yuan Cheng, Ching-Cherng Sun, National Central Univ. (Taiwan)

Collinear holographic storage system is known for simplicity and stability. The storage capacity however is limited by diffracted image quality, signal ratio per page, low diffraction efficiency, and scattering noise of recording material. The lens-array reference modulation has been proved to provide the best image quality. In this paper, we show that the signal ratio, reading power utilization, and scattering noise are also improved by lens-array modulation. Because of the trade-off between shift selectivity and diffracted image quality, an optimization of lens-array modulation is applied. Based on simulation result, we show it is possible to reaches 9TB/disc of raw data storage capacity for the recording material with M/# 60 and scattering ratio 6?10-4.

9201-38, Session PMon

Construction principles of optical data storage system on the base of computer generated Fourier holograms

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Application of holographic principles for digital information storage suggests a possibility of long-lasting safety, high density, and fast access rate of stored data. One of the major problems of the most proposed holographic memory systems is high-precision reference/object-beams optical set-up that is required to record two dimensional data pages as microholograms with challenging information density. In this article we propose to encode the standard ECMA-377 holographic memory data pages as computer-generated amplitude Fourier-holograms (CGFH), display the synthesized structures using spatial light modulator (SLM) and project them onto the photosensitive holographic medium with multiple aperture reduction. Optical projection setup of data recording system appears to be significantly simpler comparing to classical two-beams coherent systems and can be built using either coherent or incoherent light sources. This article represents the method of CGFH synthesis, the optical schemes of microholograms projection record and encoded data reconstruction, and the limitations of single CGFH information density are considered.

9201-18, Session 5

Near and far field experiments of power transfer by mode beating in plasmonic devices *(Invited Paper)*

Tobias Maletzky, Dayu Zhou, Eric Jin, Moris Dovek, Headway Technologies, Inc. (United States)

Heat assisted magnetic recording (HAMR) [1] requires a sufficiently small heat spot beyond the diffraction limit of light. This can be achieved with an optical near field source consisting of a metallic nanostructure

supporting edge plasmon polaritons (EPP [2]]).

One method to couple light from a dielectric waveguide to an EPP is mode beating [3]: complete power transfer between the pure waveguide and pure EPP modes can be accomplished in the overlap region, which is half of the beating length of the dielectric waveguide and the EPP structure.

This talk discusses a structure consisting of a hundreds of microns long rectangular waveguide and a triangular edge plasmon generator (EPG) with variable length. The structure is excited by a Laser focused at the waveguide inlet. The EPG is located at the opposite end at the waveguide outlet. By near field recording based on phase change material (PCM) evaporation [4] and far field polarization measurement, the power oscillations between the waveguide and EPG are demonstrated.

In the near field experiment, PCM is deposited on the end face of the structure. By measuring the PCM evaporation pattern the power distribution can be determined. Since the beating length of the two relevant modes in this structure is 4 µm, the measured patterns after a half beating length, one beating length and 1.5 beating lengths indicate the power oscillations. The polarization and intensity of transmitted light is also analyzed in the far field experiment, showing good correlation with simulation of coupling between waveguide and EPG.

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9201-19, Session 5

Heat assisted magnetic recording performance and integration challenges

(Invited Paper)

Chris J. Rea, Seagate Technology LLC (United States)

The commercialization of heat-assisted magnetic recording (HAMR) presents some significant technical challenges that need to be resolved before the widespread adoption of the technology can begin. In this paper, we present component performance, data from prototype drives, and update on efforts to address the key challenges around recording performance optimization, thermal management, and power requirements for HAMR recording system.

With the recent 1.0 Tb/inch2 basic technology demonstration (BTD) [1], and drive level demonstration [2] HAMR has proven to be a viable and promising technology for future magnetic data-storage products. At this point, it is important to examine HAMR limitations and extendibility. The working principle of HAMR technology is to elevate media temperature during writing [3]. The reduced media coercivity at elevated temperature provides a solution to the fundamental constraint of "writability versus thermal stability" as magnetic recording scales down. Once the "writability versus thermal stability" constraint is broken, the magnetic recording density is expected to grow, if grain size can be scaled down continuously.

The media material must provide anisotropy strong enough for stable storage at room temperature. At the same time, the HAMR head must provide an efficient heating mechanism and a sufficiently small writing spot size. Emerging near-field plasmonics technology [3] provides a viable solution for HAMR head design and efficient energy transfer to the media far below the diffraction limit.

We will expand upon some of the interactions between the recording head and the media space that bound the performance due to erasure of information in the current or adjacent tracks [4].

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9201-20, Session 5

Effects of optical properties on power delivery and self-heating in near field transducers for heat-assisted magnetic recording

Nan Zhou, Luis M. Traverso, Xianfan Xu, Purdue Univ. (United States)

To keep increasing the storage density in the next generation hard disk drives, heat-assisted magnetic recording has been developed where a near field transducer (NFT) is introduced to locally and temporally heat a sub-diffraction-limited region in the recording medium to reduce the magnetic coercivity. This allows use of very small grain in the medium while still maintaining data thermal stability. Plasmonic nanostructures made of apertures or antennas are good candidates for NFT because of the capability of subwavelength light manipulation in optical frequencies. The NFT must simultaneously deliver enough power to the recording medium with as small as possible incident laser power to reduce the self-heating effect in NFT, which could cause thermal expansion and materials failure that lead to degradation of the overall hard drive performance. In this work, we study the effect of optical properties on the absorption and coupling efficiency of two NFT designs, bowtie aperture and tapered C aperture, with the presence of recording media stack. Heat dissipation and temperature rise in NFT are also computed to investigate their dependence on materials' properties. The possibility of using alternative plasmonic materials for delivering higher power and/or reducing heating in NFT will be discussed.

9201-21, Session 5

Multi-Objective Inverse Design of Sub-Wavelength Optical Focusing Structures for Heat Assisted Magnetic Recording

Samarth Bhargava, Eli Yablonovitch, Univ. of California, Berkeley (United States)

We report using Inverse Electromagnetic Design to computationally optimize the geometric shapes of metallic optical antennas for practical use in Heat-Assisted Magnetic Recording (HAMR). This magnetic data-recording scheme relies on focusing optical energy to locally heat the area of a single datum, several hundred square nanometers on a hard disk, to the Curie temperature of the magnetic storage layer. We report multi-objective optimization of the Near-Field Transducer (NFT) geometry to overcome the challenges in realizing HAMR. First, the requirement of several mWs of optical power to be delivered to the magnetic media necessitates that the total optical power coupling efficiency from a laser diode to the hotspot be at least several percent. Second, the high Curie temperatures of the magnetic media demands that the metallic NFT be designed to not simultaneously over-heat. Third, the dependence on an optically defined thermal footprint to delimit the recording area on the magnetic media demands little background optical radiation on the disk to avoid undesired recording to adjacent tracks. One cannot design the NFT by tackling each of these challenges independently, because their respective performance metrics are tightly coupled. We present multi-objective optimizations using Inverse Electromagnetic Design in conjunction with a commercial 3D FDTD Maxwell-equations simulator, and we report the resultant optimized NFT geometries that overcome these challenges simultaneously. Also, we distributed the Inverse Electromagnetic Design software online so others can use this optimization method as a repeatable design process.

9201-22, Session 6

3D direct laser writing of petabyte optical disc *(Invited Paper)*

Eugen Pavel, Storex Technologies Inc. (Romania)

Data storage in glassy materials offers advantages of extremely long storage life, essential for data archiving. Previous reports regarding 3D optical data storage in transparent glassy and crystalline materials were obtained by femtosecond lasers.

In this presentation we report novel results for 3D recording an optical disc with ultra-high density of 6 PB (250 data layers). Multilayer 5nm nanomarks were experimentally obtained by using fluorescent photosensitive glass-ceramics and an optical head with ?=650 nm and NA=0.60. Ultra-high density optical data were recorded by focusing laser beam of a CW laser diode operating at low power (Pmax = 10 mW).

In Fig.1 we present schematic diagram of the dynamic tester, and the structure of the multilayer optical disc. A TEM image is shown in Fig.2.

Fig. 1 (a) Schematic diagram of the dynamic tester, and (b) structure of the multilayer optical disc.

The disc (?80x1.2 mm) was recorded at 9.6 m/s. We succeeded to decrease the distance between two adjacent layers up to 70 nm. Improved resolution - 5 nm, and small distance between adjacent layers -70 nm, has provided to fluorescent photosensitive glass-ceramics a data storage capacity beyond 1 Petabyte.

Fig. 2 TEM image of a cross-section of multiple 5 nm parallel lines.

In summary, we have demonstrated the writing of cylindrical structures (diameter ~ 5 nm) in three dimensions in fluorescent photosensitive glass-ceramics at a density of 6 PB/disc, or 3Pbits/in2 (250 data layers) using a red laser diode with ? = 650 nm. This performance is thousand times better than that described by any other data storage system. Results reported in this paper illustrate the potential of fluorescent photosensitive glass-ceramics in ultra-high density data storage.

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9201-23, Session 6

Prospects and philosophy for high-density optical recording *(Invited Paper)*

Thomas D. Milster, The Univ. of Arizona (United States)

In recent years, the commercial impact of optical data storage systems has been displaced by new technologies. Historically, optical data storage also displaced older technologies, like consumer magnetic tape, so it is not unexpected that the same fate could pass optical data storage technology into the "retro" domain. In this talk, the basic building blocks of optical data storage are discussed, and limits based on current understanding are presented. Then, conceptual and philosophical arguments are presented to direct intuition toward future possibilities that may provide avenues to develop displacement data storage technology. For example, current understanding puts minimum practical data mark transverse dimensions in the range of 10nm by 10nm, regardless of recording technology. At the conservative assignment of 1 bit per mark area, this mark size equates to about 1TB (10^12 Bytes) per square inch of surface area. In order to gain the attention of research investment, displacement technologies need to target a 100X improvement in data density or about 1nm by 1nm mark size, with an effective surface data density of over 100TB per square inch. Research and engineering mindsets for displacement data storage technologies should address this goal to be considered significant. Otherwise, advancements in known technologies will probably evolve to satisfy demand.

9201-24, Session 6

Optical solutions for ultra-high density data storage *(Invited Paper)*

Min Gu, Yaoyu Cao, Xiangping Li, Zongsong Gan, Swinburne Univ. of Technology (Australia)

Recognised as the key to storing soaring information, big data centres with petabytes capacities are indispensable in supporting globally booming cloudy computing & storage. However, to store equivalent amount of data with current magnetic hard drives would require infrastructures the size of a football field, which accounts for enormous energy consumption as well. Although the conventional optical data storage has revealed its unique advantages in high energy efficiency and volumetric storing ability [1], the microscope-based recording principle set up a barrier, well know as the diffraction limit of light, that traps the smallest bit size in the wavelength region, which in turn limits the current optical data storage capacity of tens of Gigabytes per disc.

In this paper, we report on our recent progress on the development of optical solution to enable an ultra-high density data storage protocol by directly breaking the diffraction limit with a super-resolution photoinduction-inhibited nanolithography (SPIN) approach [2, 3]. The SPIN technique can produce a focal spot with diffraction-unlimited size for both of recording and writing, while the capability of three-dimensional storage is maintained. For recording, we have demonstrated bits recorded as small as 33 nm, which leads to an equivalent storage capacity approaching 1 PB per disc. For reading process, the super-resolved fluorescence signal is tracked by using stimulated-emission depletion based photoluminescence process, which allows for reading bit size far less than the wavelength of the laser beam in use. In addition, we have applied parallel laser beams obtained by phase modulation to raise the throughput in data recording and enable fast accessing tightly packed bits on the disc.

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9201-25, Session 6

A high-NA solid immersion objective for imaging a Blu-ray disc and investigating subsurface damage

Victor E. Densmore III, Youngsik Kim, College of Optical Sciences, The Univ. of Arizona (United States); Thomas D. Milster, Matthew C. Wattson, Dolaphine Kwok, The Univ. of Arizona (United States)

Nano-scale resolution in miniature optical systems has been realized in the optical data storage industry. Numerical apertures greater than unity have been achieved in optical data storage research by utilizing the high index material of a Solid Immersion Lens (SIL), which increases the resolution of the backing objective by factor that is related to the refractive index of the SIL. In this research, a custom Hyper-Blu- Disc (HBD) NA=1.4 SIL objective is utilized for high-fidelity readout of data pits beneath a 100mm thick cover layer on an optical Blu-Ray Disc. If realized commercially, the increase in data density could be 3X today's Blue-Ray technology. A distinct difference between this work and other work with SILs in optical data storage is the relatively thick cover layer of 100mm. A custom silicon actuator is designed for controlling the SIL gap height. Recently, there has been interest in discovering new ways to apply the technology and methods used in optical data storage for other means. The inherent design of the HBD objective to image through a shallow layer of dielectric material may lend itself to be used as an effective means for characterizing subsurface damage in optical materials. This research will furthermore investigate the HBD objective as a means for detecting subsurface damage.

9201-26, Session 7

Decoupling direct tracking control system for super-multilayer optical disk *(Invited Paper)*

Yukinobu Tanaka, Hitachi, Ltd. (Japan)

This paper presents the decoupling direct tracking control method for the super multi-layer optical disk. The disk includes multiple recording layers and a servo layer with a guiding groove, and data is recorded on each recording layer right above the groove of the servo layer by use of two laser beams. Therefore, keeping the relative position of the focal points on the recording layer and the servo layer is important in order to record data on the accurate position of the recording layer. However, some disturbances such as disk tilt or lens shift might cause displacement between the two focal points. And due to scratches or finger prints on the disk surface, two focal points' coupling actions destabilize the tracking control.

So we developed new tracking control method for preventing any displacement and destabilization by the coupling action. In this method, the tracking control is performed by regarding a string of previous recorded marks on a recording layer as a virtual track and wobble of the groove on the servo layer is used for disk rotation control. And it's applied the decoupling model derived from the state space model of an optical pick up.

We conducted the verification study by applying the method to our actual equipments with this tracking control method, and confirmed the present permitted limit of disk tilt has expanded from 0.05 to 0.7 degrees and two focal points' coupling actions have reduced to -20 dB over the all frequency bandwidth.

9201-27, Session 7

Micromachining technologies for application in optical storage system *(Invited Paper)*

Pei Li, Luping Shi, Jing Pei, Longfa Pan, Tsinghua Univ. (China)

With rapid development of micromachining technologies, more and more optical and mechanical components are miniaturized and integrated in the optical storage system. Among them, lens positioning systems are indispensable components for writing and reading in optical drives and discs. Using micromachining technologies to miniaturize lens positioning systems, researchers attempted to realize micro actuators using plenty of micro actuation methods. Such micro actuator systems provide large decoupling tracking and focusing adjustment ranges of lenses, as well as small volumes. Furthermore, polymer microlenses with smooth surface and relatively high aspect ratio have been obtained and integrated on the micro actuators, presenting an important step for total integration of a micro optical head. In this summary we review the recent development of micromachining technologies for the fabrication of micro components in optical storage system with the focus on our recent progress. Integration of micro optical and mechanical components is discussed for the application to the optical storage system.

9201-28, Session 7

Metallic resist for phase change lithography *(Invited Paper)*

Bi Jian Zeng, Jun Zhu Huang, Ri Wen Ni, Nian Nian Yu, Wei Wei, Yang Zhi Hu, Zhen Li, Xiangshui Miao, Huazhong Univ. of Science and Technology (China)

No Abstract Available

9201-29, Session 7

High-density data recording on the thin nanocomposite films by laser thermo-lithography

Andriy Kryuchyn, Ivan Gorbov, Institute for Information Recording (Ukraine); Konstantin P. Grytsenko, V.E. Lashkaryov Institute of Semiconductor Physics (Ukraine); Olexei Tolmachev, Institute of Organic Chemistry (Ukraine)

In conventional photochemical data recoding process all irradiated media are exposed and transformed. In this case, data recording density is restricted by diffraction limit. In high-density thermo-lithography data recording the recording process executes only in area where phase transition occurs. The size of the area can be significantly smaller than the laser spot size, which makes it possible increasing the density of optical recording. This recording method requires using a proper recording media with predefined characteristics. In this work intra-ionic conjugated systems (dyes) characterized by intensive and selective absorption in the spectral region 390-410 nm were elaborated. These dyes are able to be evaporated by 405 nm laser radiation. The nanocomposite films were created on base of organic positive photoresist which is also sensitive to 405 nm radiation and added synthesized dyes with 1 – 5 % concentration. The 200 nm layer of nanocomposite film was layered on glass substrates.

The pits with 250 – 300 nm width were performed on the thin organic nanocomposite films by 405 nm laser beam focused by 0.85 NA lens. The pits have a tapered form with 50 – 100 nm bottoms. The nanocomposite film with obtained pits was used as a mask for reactive ion-beam etching of glass substrate. The 150 – 200 nm pits were performed on the substrate surface in the result of the etching. Proposed laser thermo-lithography method can be used for creation of master discs for next generation optical media.

9201-30, Session 8

Progress in second-generation holographic data storage *(Invited Paper)*

Mark R. Ayres, Ken E. Anderson, Fred Askham, Brad Sissom, Akonia Holographics, LLC (United States)

Holographic data storage (HDS) remains an attractive technology for big data. We report on recent results achieved with a demonstrator platform incorporating several new second-generation techniques for increasing HDS recording density and speed. This demonstrator has been designed to achieve densities that support the multi-terabyte storage capacities required for a competitive product. It leverages technology from an existing state-of-the-art pre-production prototype, while incorporating a new optical head designed to demonstrate several new technical advances.

The demonstrator employs the new technique of dynamic aperture multiplexing in a monocular architecture. In previous a report, a monocular system employing angle-polytopic multiplexing achieved a recording density over 700 Gbit/in2, exceeding that of contemporaneously shipping hard drives. Dynamic aperture multiplexing represents an evolutionary improvement with the potential to increase this figure by up to 300%, while still using proven angle-polytopic multiplexing in a monocular architecture.

Additionally, the demonstrator is capable of two revolutionary advances in HDS technology. The first, quadrature homodyne detection, enables the use of phase shift keying (PSK) for signal encoding, which dramatically improves recording intensity homogeneity and increases SNR. The second, phase quadrature holographic multiplexing, further doubles density by recording pairs of holograms in quadrature (QPSK encoding).

We report on the design and construction of the demonstrator, and on the results of current recording experiments.

9201-31, Session 8

Shift-peristrophic multiplexing for holographic data storage *(Invited Paper)*

Hiroyuki Kurata, Jun Mori, Yu Tsukamoto, Keiko Yamamoto, Shuhei Yoshida, Manabu Yamamoto, Tokyo Univ. of Science (Japan)

In this article, we examined the possibilities for high-density recording using a novel multiplexing method, which combines shift multiplexing with spherical reference wave with peristrophic multiplexing. The shift multiplexing is expected to improve recording density, as shift multiplexing in multiple dimensions can be achieved using a spherical reference wave. However, it has been found in previous studies that the shift selectivity in the vertical direction perpendicular to the recording tracks is insufficient, thus inhibiting high density development, although the shift selectivity is excellent along the track direction of the medium as well as the film thickness direction. We therefore combined peristrophic multiplexing with shift multiplexing, a method of multiplexing that involves changing the incident direction of signal and reference wave and superposing. The potential for achieving high target storage capacity is demonstrated through numerical analysis and experiments.

9201-32, Session 8

Quantitative modeling of the reaction/diffusion kinetics of holographic photopolymers

Benjamin A. Kowalski, Adam C. Urness, Michael C. Cole, Univ. of Colorado at Boulder (United States); William L. Wilson, Univ. of Illinois at Urbana-Champaign (United States); Robert R. McLeod, Univ. of Colorado at Boulder (United States)

A general strategy for characterizing the reaction/diffusion kinetics of holographic photopolymer media is proposed, in which key processes are decoupled and independently measured. This strategy is demonstrated for a range of model materials similar to commercial media, yielding quantitatively accurate predictions of index response. Crucially, this strategy enables prediction of the potential Dn of a material solely on the basis of its chemical components. The degree to which a material does not reach this potential reveals the fraction of monomer that has participated in unwanted reactions, reducing spatial resolution and lifetime.

9201-33, Session 8

Homodyne detection of holographic memory systems

Adam C. Urness, Univ. of Colorado at Boulder (United States) and Univ. of Illinois Urbana-Champaign (United States); Mark R. Ayres, Akonia Holographics, LLC (United States); William L. Wilson, Univ. of Illinois at Urbana-Champaign (United States)

We present a homodyne detection system implemented on a page-wise holographic memory architecture. Homodyne detection of holographic memory systems enables both phase quadrature multiplexing, doubling the address space, and phase modulation, which increases the signal to noise ratio (SNR) to further enhance the data capacity.

9202-51, Session PMon

Considerations for application of Laguerre-Gaussian beam wave in optical wireless communication

Kayo Ogawa, Aya Saito, Japan Women's Univ. (Japan)

In late years, utilization of spatial modulation elements has made it possible to easily produce Laguerre-Gaussian beam waves and various applications thereof have been begun. Analysis of spatial propagation of Laguerre-Gaussian beam wave has been advanced. No examination, however, has been made so far as to what mode is suitable to the optical wireless communication. Therefore, we has examined the influences of the scintillation can be reduced through the use of Laguerre-Gaussian beam wave as carrier. In this report, a comparison in propagation loss was made between Gaussian beam wave conventionally used in the optical wireless communication and Laguerre-Gaussian beam wave. As a result of the examinations, we obtained that the propagation losses of any of the Laguerre-Gaussian beam waves are smaller than those of the Gaussian beam waves. It is also observed that the propagation loss of (5, 3) Laguerre-Gaussian beam wave is particularly small among those.

In addition, we has examined the optimum combination of the optical variables including the wavelength, the spot size radius, and the receiver aperture, in order to reduce the influences of the scintillation which is one of factors that deteriorate the communication quality of the optical wireless communication. As a result of the examinations, the optimum spot size radii and the optimum receiver apertures have been successfully found.

9202-62, Session PMon

Materials and designs in multifunctional, injectable optoelectronic devices for optogenetics

Junsik Kim, Byeonghak Park, Hyejin Jang, Sungkyunkwan Univ. (Korea, Republic of); Tae-il Kim, Sungkyunkwan Univ. (Korea, Republic of) and Ctr. for Neuroscience Imaging Research (Korea, Republic of)

The techniques of optogenentics provide unique opportunities for studying many topics of fundamental interest in neuroscience. Existing mechanisms for delivering light into the tissues of living animals impose, however, significant constraints on the types of experiments that are possible. In this presentation, we describe the materials science of a class of implantable, multifunctional, microscale devices that incorporate wireless powering and control strategies, to allow less-invasive study of intact neural systems in naturally behaving animals. The enabled modes of use are impossible to realize using standard approaches that rely on rigid, long, glass fiber optics coupled to external, bulky light sources. Our systems exploit ultrathin, flexible substrates populated with microscale inorganic light emitting diodes (LEDs) together with electrophysiological sensors, all mounted on removable plastic needles that facilitate insertion into the tissue. Detailed experimental and theoretical studies of the operation, ranging from heat flow aspects to inflammation assessments and comparison to conventional devices, illustrate the unique features of this technology. We exploit the devices for light stimulation of catecholaminergic cell populations selectively expressing channelrhodopsin-2, in awake, ambulatory mice. The results suggest that the reported materials and device designs have promise not only in optogenetic applications but also in other areas of implantable diagnostics and therapeutics.

9202-63, Session PMon

Performance evaluation of SE solar cells with laser opening and single-step diffusion

Jyh-Jier J. Ho, National Taiwan Ocean Univ. (Taiwan)

In summary, we explore the influence of sheet resistances on SE solar cells with laser opening and single-step POCl3 diffusion. The best cell with conversion efficiency of 16.20 % for SE2 is obtained, with VOC of 612.52 mV and F.F. of 75.83 % which are the largest among six samples too. It features a solar cell emitter with a sheet resistance pair of (40/81) ?/Sq in heavily doped region and lightly doped region respectively. While the longest lifetime of 9.313 ?s is achieved by SE6 corresponding to the largest JSC of 35.16 mA/cm2. Furthermore, compared the data of Table I, Table II and Table III, there are some irregular variation tendencies for I-V parameters and EQE of the six cells SE1 to SE6. The thickness of passivation layer, forming by thermal oxidation with different duration, indeed affects characteristics of SE mc-Si solar cells. The irregular variation tendency of some parameters shall be studied further on.

9202-64, Session PMon

Dimensional stability of materials based on Portland cement at the early stages

Angelica M. Mesa Yandy, CONICET La Plata (Argentina) and Ctr. de Investigaciones Ópticas (Argentina) and Univ. Nacional de la Plata (Argentina); Raúl L. Zerbino, CONICET La Plata (Argentina) and Univ. Nacional de la Plata (Argentina); Graciela M. Giaccio, Comisión de Investigaciones Científicas (Argentina) and Univ. Nacional de la Plata (Argentina); Nelida A. Russo, Comisión de Investigaciones Científicas (Argentina) and Ctr. de Investigaciones Ópticas (Argentina); Ricardo Duchowicz, CONICET La Plata (Argentina) and Comisión de Investigaciones Científicas (Argentina) and Univ. Nacional de la Plata (Argentina)

The study of the expansion or contraction processes in the fresh state is a requirement for some commercial grouts specially designed for sealing parts and structural elements. In recent years, much attention has been paid to cases of early cracking of pastes, mortars and concretes made of Portland cement. However, they are very limited methods to evaluate dimensional changes in plastic state (fresh, before the setting of the material occurs), since any device that is fixed on the fresh material causes alterations on it. An alternative to make such determinations is provided by the optical methods like the use of the Fizeau interferometer and fiber Bragg gratings (FBG) sensors. In this work, vertical and horizontal measurements using the mentioned interferometer and / or FBGs were performed, and a mechanical comparator was used in order to contrast results. Two types of commercial grouts with different compositions were studied in order to characterize expansion or contraction processes. The temporal evolution of the dimensional changes of the sample and the analysis of the observed behavior are included in the work.

9202-65, Session PMon

Method for separating video camera motion from scene motion for constrained 3D displacement measurements

Leo R. Gauthier Jr., Melissa E. Jansen, John R. Meyer, Johns Hopkins Univ. Applied Physics Lab., LLC (United States)

Camera motion is a potential problem when a video camera is used to perform dynamic displacement measurements. If the scene camera moves at the wrong time, the apparent motion of the object under study can easily be confused with the real motion of the object. In some cases, it is practically impossible to prevent camera motion, as for instance, when a camera is used outdoors in windy conditions. A method to address this challenge is described that provides an objective means to measure the displacement of an object of interest in the scene, even when the camera itself is moving in an unpredictable fashion at the same time. The main idea is to synchronously measure the motion of the camera and to use those data ex post facto to subtract out the apparent motion in the scene that is caused by the camera motion. The motion of the scene camera is measured by using a reference camera that is rigidly attached to the scene camera and oriented towards a stationary reference object. For instance, this reference object may be on the ground, which is known to be stationary. It is necessary to calibrate the reference camera by simultaneously measuring the scene images and the reference images at times when it is known that the scene object is stationary and the camera is moving. These data are used to map camera movement data to apparent scene movement data in pixel space and subsequently used to remove the camera movement from the scene measurements.

9202-1, Session 1

Fiber optic liquid level sensor system for aerospace applications *(Invited Paper)*

Alex A. Kazemi, The Boeing Co. (United States); Chenging Yang, Shipping Chen, University of Maryland (United States)

Detection of the liquid level in fuel tank becomes a critical element for the safety and efficiency in aviation operations. Two liquid level sensing techniques are presented in this paper. The first technique is based on optical fiber Long Period Gratings (LPG). In this technique, the full length of a specially fabricated fiber is the body of the probe because the length of the sensing fiber that is submerged in the liquid can be detected by the interrogation system. The second system based on Total Internal Reflection (TIR) uses optical fibers to guide light to and from an array of point probes. These probes are specially fabricated, miniature optical components which reflects a substantial amount of light back into the lead fiber when the probe is gas but almost no light when it is in liquid. A detailed theoretical study by computer simulation was carried out on these two techniques in order to determine which technique was more suitable for experimental investigation. The study revealed that although the first technique may provide more potential benefits in terms of weight and easy installation; a number of technical challenges make it not suitable for a short term solution. The second, probe array based technique, on the other hand, is more mature technically. The rest of the research program was therefore focused on the experimental investigation of the probe array detection technique and the test results are presented in this paper.

9202-2, Session 1

Eye readable metal hydride based hydrogen tape sensor for health applications

Bernard Dam, Peter Ngene, Herman Schreuders, Technische Univ. Delft (Netherlands)

Reliable and low-cost hydrogen sensors are warrented for applications in the hydrogen economy, industrial processes, space industries, environmental pollution detection, and biomedical fields. Here, a new type of optical detector that indicates the presence of hydrogen in a concentration range from 5 ppm to 0.1 vol% H2 merely by a reversible and tunable color change is reported. The device takes advantage of the reversible change in optical properties of a Pd-capped Y thin film upon exposure to H2, while the color is tuned using the interference of light reflected between the Y and Pd layers. In this way, an eye-readable optical sensor that circumvents the need for electronics and external digital readouts is created. The H2 detector also works in humid and oxygen rich environments. Therefore, the device has the potential to be used for chemical and also biochemical/biomedical H2 sensing applications such as breathe hydrogen tests.

9202-3, Session 1

A novel temperature-compensated FBG-based sensor with variable sensitivity

Raffaella Di Sante, Univ. degli Studi di Bologna (Italy); Filippo Bastianini, Sestosensor srl (Italy); Lorenzo Donati, Paolo Proli, Univ. degli Studi di Bologna (Italy)

In this work, a novel Fiber Bragg Grating (FBG) sensor device is proposed for strain detection with adjustable full-scale sensitivity. The novel, patented device is characterized by the possibility of moving the installation flanges with respect to the internal fixed FBG sensing length in order to adjust the full scale measurement range and/or the device overall strain sensitivity. The device structure is furthermore compatible with the possibility of implementing the compensation of the FBG thermal drift according to the known technique of reducing the FBG pre-strain by means of the thermal expansion of a solid block glued on the fiber in prestressed region outside the grating. In the novel design the compensation block is suspended in a separate cavity filled by a damping fluid in order to overcome the typical limitations that make compensated sensors traditionally not able to survive to shocks and vibrations. The sensitivity to strain at different temperatures is studied experimentally using a special calibration test bench in laboratory conditions.

9202-4, Session 1

Hydrogen leak detection: a comparison between fiber optic sensors based on different designs. *(Invited Paper)*

Nicolas Javahiraly, Cedric Perrotton, Univ. of Strasbourg (France)

We present a study of a fiber optic sensor for leak detection based on Surface Plasmon Resonance (SPR) where the spectral modulation of the light transmitted by the fiber allows to detect hydrogen on the environment.

The study focuses on the improvement of the sensitivity and the detection dynamic range of SPR based hydrogen sensors. Our goal is to figure out how to decrease the minimum level and to increase the maximum level of detection. In addition, we'll quantify the hydrogen concentration. From the literature analysis and from our results, it has been shown that the dynamic range of the hydrogen sensor is related to the Pd pressure composition isotherms (pcT). This study presents an exhaustive comparison between fiber optic sensors based on the association of Pd/Si/Ag materials and a fiber optic sensor based on the Mg-Ti alloys.

9202-5, Session 1

Integrated optical hydrogen and temperature sensors on silicon-on-insulator platform

Muhammad Z. Alam, Nicholas Carriere, Mo Mojahedi, J. S. Aitchison, Univ. of Toronto (Canada)

Hydrogen is odorless, colorless and forms an explosive mixture with air over a wide range of concentrations (4 to 75%). A compact, reliable and safe hydrogen sensor is required for the existing and emerging applications of hydrogen including aerospace and fuel cells. An optical

sensor is an attractive option for hydrogen sensing because of its compactness, immunity from electromagnetic interference, and inherent safety. In this work we present the results of experimental demonstration of a Pd-based hydrogen sensor and a ring resonator based temperature sensor on a silicon-on-insulator platform. The hydrogen sensor consists of a ridge waveguide with a very thin coating of Palladium. We fabricated and tested hydrogen sensor with various palladium film thicknesses, and found that for a 2 nm thick palladium film, the sensor response time is approximately 10 sec and it suffers little from hysteresis effect for this film thickness. The sensor results were repeatable under hundreds of cycles of exposure to hydrogen. The response of the hydrogen sensor is affected by variation of temperature, and this effect must be considered in a real life application of the hydrogen sensor. To overcome this limitation we design and experimentally demonstrate a temperature sensor on SOI using a ring resonator, which shows good sensitivity over a wide range of temperature. The hydrogen sensor and the temperature sensor can be integrated on the same chip to implement a hydrogen sensor capable of reliably measuring hydrogen concentration under varying temperature.

9202-7, Session 2

Development of internal components for M38999 type connectors, for use in advanced photonic applications and with specialty optical fibers

Alan Whitebook, Diamond USA Inc. (United States); Francois Caloz, Diamond SA (Switzerland)

This presentation outlines development work performed to produce internal components (connector insert assemblies & optical terminus assemblies) to be fit into MIL-DTL-38999, or commercial off the shelf (COTS) equivalent, connector housings.

Connectors modified with these internal components are then suitable for optical termination and transmission through specialty fibers such as polarization maintaining, small core single-mode, and others, with the ability to achieve high levels of performance in the areas of Insertion Loss, Return Loss, Extinction Ratio (as applicable) and Power Handling Capability (as applicable.)

Technical details are presented to illustrate features within the optical terminus, and its insert cavity, which serve to allow for fiber/ferrule polar orientation, concentricity of mated termini ferrules and fibers terminated within, and other attributes designed to support optical performance goals.

Finally, optical performance data is given and discussed to illustrate results achieved by production of evaluation cable assemblies.

9202-8, Session 2

Application suitability and reliability of harsh environment fiber optic interconnects

William M. Reid, Amphenol Fiber Systems International (United States)

Severe environments, demanding performance and cost effectiveness characterize current harsh environment system interconnect needs. The increasing use of fiber optics in these applications mandates reliable, safe and efficient fiber optic (FO) interconnect systems.

Reliability, safety, bandwidth, and environmental requirements necessitate the transition from copper wire based to fiber optic based systems. Discussed are the technologies, environments, and performance requirements applicable to these applications, along with the trade decisions necessary to implement solutions.

This paper addresses harsh environment fiber optic reliability requirements, fiber optic reliability characterization, potential FO interconnect failure modes, and the how to quantify fiber optic reliability. A case study is presented that encompasses the applicable environments for such interconnects, quantifies the inherent reliability of the FO interconnect system in such environments, and provides fiber optic interconnect reliability risk mitigation strategies. FO interconnect failure prediction is also discussed.

9202-9, Session 2

Use of the characteristic Raman lines of toluene (C7 H8) as a precise frequency reference on the spectral analysis of gasoline-ethanol blends

Nicolas Javahiraly, Valentin Ortega Clavero, Univ. of Strasbourg (France); Andreas Weber, Werner W. Schröder, Hochschule Offenburg (Germany); Patrick Meyrueis, Univ. de Strasbourg (France); Dan Curticapean, Offenburg University of Applied Sciences (Germany)

In order to reduce some of the toxic emissions produced by internal combustions engines, the fossil-based fuels have been combined with less harmful materials in recent years. However, the fuels used in the automotive industry generally contain different additives, such as toluene, as anti-shock agents and as octane number enhancers. These materials can cause certain negative impact, besides the high volatility implied, on public health or environment due to its chemical composition.

Toluene is an additive widely used in the commercially-available gasoline-ethanol blends. Despite the negative aspects in terms of toxicity that this material might have, the Raman spectral information of toluene can be used to achieve certain level of frequency calibration without using any additional chemical marker in the sample or any other external device. Moreover, the characteristic and well-defined Raman line of this chemical compound at 1003cm-1 (even at low v/v content) can be used to quantitatively determine certain aspects of the gasoline-ethanol blend under observation.

Using an own-design Fourier-Transform Raman spectrometer (FT-Raman), we have collected and analyzed different commercially-available and laboratory-prepared gasoline-ethanol blends. By carefully observing the main Raman peaks of toluene in these fuel blends, we have determined the frequency accuracy of the Raman spectra obtained. The spectral information is presented in the range of 0cm-1 and 3500cm-1 with a spectral resolution of 1.66cm-1. The Raman spectra obtained present a reduced frequency deviation (≤0.4cm-1 in the less favorable case) in comparison to the standard Raman spectra from toluene provided by the ASTM.

9202-10, Session 2

Novel optical encoder for harsh environments

Bernard C. Kress, USI Photonics Inc. (United States); Vincent Brac de la Pierriere, Univ. de Strasbourg (France)

We present a novel optical encoder architecture well suited for harsh environments.

With conventional optical encoders the limitation come from source stability over temperature ranges (such as LED or laser), detector stability over temperature ranges, and vibrations/shocks over the encoder disk (rotational) or encoder strip (linear).

In this novel architecture we decouple the encoder substrate to the source and detector. In a first implementation we are targeting a 20 bits hybrid incremental/absolute rotational encoder.

The encoder substrate is located directly on the shaft, whereas the source and detector(s) are located far away form that shaft. Our architecture allows wobbling and lateral misalignements, as well as large temperature swings.

The design techniques, modeling and prototype fabrication are presented.

9202-11, Session 3

The segmentation of the HMD industry: smart glasses, gaming devices, professional AR, and defense *(Invited Paper)*

Bernard C. Kress, Ehsan Saeedi, Google (United States)

The HMD (Head Mounted Display) industry is not new by any mean , but has been relegated to the defense sector for more than 3 decades, before being introduced as consumer electronics wearable devices.

Due to its democratization, the HMD industry is currently going through a market segmentation process, proposing wearable computing devices targeted for very different applications, and addressing various fields such as:

- smart glasses (see through and non see through, small FOV)
- gaming devices (mainly non see through, large FOV large resolution)
- professional HMDs (law enforcement, firefighting, medical, engineering - see through, augmented reality, IR sensors)
- defense (see through, augmented reality, very large FOV and very large resolution)

We will review the various optical architectures developed by the HMD industry today on the basis of such market segmentation.

9202-12, Session 3

Monolithic light guide optics enabling new user experience for see-through AR glasses

Khaled Sarayeddline, OPTINVENT S.A. (France)

This paper describes the performances of mold light guide based see-through optics for the production of AR glasses for commercial and professional applications. A monolithic thin mold light guide with surface structure mirror array extracts and project bright and large virtual image into the user eye of sight.

9202-14, Session 3

Parity-time (PT) symmetry structures implementing non-reciprocal diffraction

Bernard C. Kress, USI Photonics Inc. (United States); Mykola Kulishov, HTA Enterprises (United States)

We review our work regarding a new class of couplers and resonators that employ the concept of Parity-Time (PT) symmetry in optics. PT structures can be implemented as diffractive gratings having complex refractive index profiles.

PT-symmetric materials can produce interesting and unusual optical functionality. These include double refraction and “nonreciprocal” diffraction, or unidirectional Bloch oscillations.

We give an overview of the state-of-the art in this exciting new field, with a particular emphasis on our own work dealing with more advanced structures that contain PT symmetry gratings – more specifically grating-assisted couplers and resonant cavities, and see through optics that can be implemented in various imaging devices.

9202-15, Session 4

Environmental tests of antireflective surface structures on windows for high energy laser applications *(Invited Paper)*

Lynda E. Busse, Jesse A. Frantz, Shyam S. Bayya, L. Brandon Shaw, U.S. Naval Research Lab. (United States); Menelaos K. Poutous, Rajendra Joshi, The Univ. of North Carolina at Charlotte (United States); Ishwar D. Aggarwal, Sotera Defense Solutions, Inc. (United States); Jas S. Sanghera, U.S. Naval Research Lab. (United States)

The use of traditional antireflective coatings to reduce Fresnel reflection losses on windows for high energy laser applications is limited by optical damage under high power irradiation as well as damage to the coatings in operational environments. We have developed new methods to fabricate antireflective surface structures (ARSS) directly on the surfaces of optics to reduce reflection losses, so as to avoid coatings made with dis-similar materials. We will present recent results that demonstrate excellent ARSS performance on fused silica windows of sizes approaching practical diameters (10 to 30 cm) for applications as exit apertures for high energy laser systems. Reflection losses below 0.5% have been obtained for ARSS on 10 cm. diameter silica windows, and laser damage testing has yielded damage thresholds of 100 J/cm2 at 1.06 μm for these windows. In addition, we will present environmental testing results obtained on windows with ARSS, including rain and sand erosion tests as well as salt fog testing. These results are of interest for practical use of these windows for high-energy laser exit apertures, for which robust optical performance is needed.

9202-16, Session 4

Optical and piezoelectric properties of p-type ZnO nanowires on transparent flexible substrate for energy harvesting

Guocheng Liu, Univ. of Waterloo (Canada); Man Chun Tam, Lilei Hu, Karim El-Rayesb, University of Waterloo (Canada); Qiuquan Guo, Jun Yang, The University of Western Ontario (Canada); Nezih Mrad, National Defence Headquarters (Canada); Dayan Ban, Univ. of Waterloo (Canada)

High-quality nanowires (NWs) with controlled structure grown on transparent flexible substrate have attracted intensive research interest on harvesting solar and mechanical energies. Investigating their optical and piezoelectric properties is essential for this application. In this paper, the well-aligned and vertical Lithium (Li) doped p-type ZnO NWs were grown on micro-patterned transparent flexible polyethylene naphthalate (PEN) substrate by hydrothermal and electrochemical deposition methods at low temperature. A thin aluminum-doped ZnO (AZO) was covered on the flexible substrate, serving as a good seed layer and a transparent conductive oxide layer. By varying the seed layer thickness, the individual NW diameter, density and alignment can be controlled. The effect of doping on the optical band-gap, crystalline quality and the Schottky barrier was investigated by photoluminescence (PL), X-ray diffraction (XRD) spectroscopy and piezoelectric characterization. Acceptor induced red shift of band gap for the doped ZnO nanowires were found by PL measurement at room temperature. XRD results indicated that the qualities of ZnO nanowires were improved by proper incorporation of Li dopants. Piezoelectric characterization using conductive atomic force microscope (C-AFM) with Pt coated tips on doped and undoped ZnO NWs showed that the Schottky barrier changes with the Li doping concentration. To improve the quality of ZnO NWs, different techniques, such as annealing and oxygen plasma, were investigated. High performance ZnO NWs on transparent flexible PEN substrate could be obtained by proper Li doping concentration and post-treatment.

9202-17, Session 4

Investigation on harsh environmental effects on polymer fiber optic link for aircraft systems

Sandy Cherian, Holger Spangenberg, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Reinhard Caspary, Technische Univ. Braunschweig (Germany)

To integrate polymer fiber based physical layer for avionic data network, the impact and cause of harsh environments on polymer fiber optic components and harness are necessary to understand. Since temperature and vibration have a significant influence , we investigate the variation in optical transmittance and monitor the endurance of different types of connector and splices under extreme aircraft environments. Presently, there is no specific aerospace standard for the application of polymer fiber and components in the aircraft data network. Therefore, in the paper we examined and defined the thermal cycling and vibration measurement set up and methods to evaluate the performance capability of the physical layer of the data network. Also we presented some of the interesting results observed during the measurements.

9202-18, Session 4

Analysis and comparison of experimental and simulated results for an omnidirectional free space optical receiver architecture

Syed H. Murshid, Grogory L. Lovell, Michael F. Finch, Florida Institute of Technology (United States)

Lasercomm or Free Space Optical (FSO) communication has the potential to provide fiber optic data rates without the need for wired physical connectivity. This paper investigates the feasibility of an Omnidirectional FSO (O-FSO) communications link that utilizes fiber bundles for improved omni-directionality and compares experimental data with modeled results. Current state of the art O-FSO link ranges are limited to 100 meters or so, with data rates of only a few100 kbits/sec. The proposed architecture is formed from commercially available fiber bundle that collects omnidirectional light due to the hemispheric nature of the fiber bundle by exploiting the acceptance cones of the individual fiber exposed to the optical radiation. The experimental transmitter is composed of an LED source that is driven by an On-Off-Keying signal. This paper presents the received optical power while varying the range between the transmitter and receiver. The omni-directionality of this architecture is also verified. The measured results are then compared to the model predictions for omni-directionally and range.

9202-19, Session 4

The health risks associated with energy efficient fluorescent, LEDs, and artificial lighting

Allen S. Panahi, Pentair Ltd. (United States)

With the phasing-out of incandescent lamps in many countries, the introduction of new LED based light sources and luminaires sometimes raises the question of whether the spectral characteristics of the LED and other energy saving fluorescent lamps (such as CFLs) are suitable to replace traditional incandescent lamps. These concerns are sometimes raised particularly for radiation emissions in the UV and blue parts of the spectrum. This paper aims to address such concerns for common ‘white light’ sources typically used in households and other general lighting used in the work place. Recent studies have shown that women working the night shift night have an increased probability of developing breast cancer. We like to report on the findings of many studies done by the medical professionals, in particular the recent announcements of the AMA in the US and many studies conducted in the UK, as well as the European community to increase public awareness on the long term health risks of the optical and opto-biological effects on the human health caused by artificial lighting.

9202-20, Session 5

Light weight, high-speed, and self-powered wireless fiber optic sensor (WiFOS) structural health monitor system for avionics and aerospace environments *(Invited Paper)*

Edgar A. Mendoza, Yan Esterkin, Connie Kempen, Sunjian Sun, Redondo Optics, Inc. (United States)

This paper describes recent progress towards the development of an innovative light weight, high-speed, and self-powered wireless fiber optic sensor (WiFOS™) structural health monitor system suitable for the onboard and in-flight unattended detection, localization, and classification of load, fatigue, and structural damage in advanced composite materials commonly used in avionics and aerospace systems. The WiFOS™ system is based on ROI’s advancements on monolithic photonic integrated circuit microchip technology, integrated with smart power management, on-board data processing, wireless data transmission optoelectronics, and self-power using energy harvesting tools such as solar, vibration, thermoelectric, and magneto-electric.

The self-powered, wireless WiFOS™ system offers a versatile and powerful SHM tool to enhance the reliability and safety of avionics platforms, jet fighters, helicopters, commercial aircraft that use lightweight composite material structures, by providing comprehensive information about the structural integrity of the structure from a large number of locations. ROI’s WIFOS™ system represents a new, innovative, and reliable solution for next generation self-power wireless fiber optic sensors applications for use in structural health monitoring, diagnosis and prognostics of DoD and commercial infrastructures. Its miniaturized package, self-power operation, state-of-the-art wireless data communications architecture, smart signal prognostics, and affordable price make it a very attractive solution for a large number of SHM/NDT applications. Immediate SHM applications are found in rotorcraft and aircraft, ships, submarines, and in next generation weapon systems, and in commercial oil and petrochemical, aerospace industries, civil structures, power utilities, portable medical devices, and biotechnology, homeland security and a wide spectrum of other applications.

9202-21, Session 5

Results of sapphire optical fiber strain and temperature sensor testing up to 1600 C for next-gen nuclear reactors

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There currently exists no method to reliably characterize the mechanical properties of advanced refractory materials used in the core of next-generation nuclear reactors at accident-condition temperatures which can reach as high as 1600 °C. This existing technology gap presents a tremendous challenge to licensing this type of reactor due to a greater need for health monitoring, maximizing autonomous operation, improved safety, and extended service life. In order to meet these challenges, Lambda Instruments, Inc. is developing extremely high-temperature, radiation hardened strain and temperature sensors based on the unique properties of single-crystal sapphire optical waveguides capable of continuous operation up to 1600 °C.

Both intrinsic and extrinsic Fabry-Perot strain and temperature sensor designs are being tested in house at temperatures exceeding 1600 °C

and off-site within university-operated test reactors providing a maximum neutron exposure exceeding 3.0 x1019 n-cm-2. As this will be the highest total dose for sapphire-based sensors that has ever been reported in the literature, we expect that successful completion of this objective will significantly advance the state of the art and knowledge in this area.

9202-22, Session 5

Distributed fiber optic sensor based on correlation coded Brillouin scattering for long range condition monitoring

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Brillouin Optical Time Domain Analysis (BOTDA) is a powerful technique for sensing the strain or temperature over a long distance in an optical fiber [1]. It is well known that the spatial resolution of the sensor depends on the pulse-width of pump used. Consequently, the short pulses required to support high spatial resolution compromises the range of measurement. Correlation techniques in which the pump is modulated by a coded sequence and the response is correlated with the same sequence to obtain the time domain response can be used to overcome such limitations [2].

In optical systems, an unipolar sequence is typically preferred as they can be directly used for modulating the laser. However, bipolar orthogonal codes show excellent autocorrelation properties leading to better resolution for Correlation BOTDA while the unipolar codes will always have some side lobes in their autocorrelation. In this paper, we carry out simulations predicting that bipolar codes (Golay) will be more suitable for long range conditional monitoring compared to unipolar codes (Hadamard-Cyclic). Such results have been experimentally validated and we find that orthogonal bipolar codes provides better resolution compared to unipolar codes though the processing time needed for bipolar codes is relatively longer. We have successfully demonstrated the detection of a 10 m long event at the middle of a 50 km long sensing fiber using Golay codes.

References

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9202-23, Session 5

Pest damage estimation using thermal imaging

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Infrared energy is the part of electromagnetic radiation that we perceive as heat and using Infrared thermography we can visualize temperature distribution across a body. Thermal imaging has been used extensively and is well established in aerospace, military and industry, and has a huge potential in agriculture as well. In some fruits and vegetables it is difficult to visually identify the ones which are pest infested. In this article, we propose and show for the first time how a thermal imaging camera can be used detect the level of pest damage in fruits and vegetables. Our key idea relies on the fact that there is a difference in the heat capacity of normal and damaged ones. This paper presents the concept of using infrared thermal imaging in non-destructively identifying pest damage levels of fruits and vegetables.

9202-24, Session 5

High speed all-optical PRBS generation using binary phase shift keyed signal based on QD-SOA

Wenbo Li, Hongyu Hu, Niloy K. Dutta, Univ. of Connecticut (United States)

PRBS (pseudo random binary sequence) generation is important for a wide range of applications including communication systems, optical logic systems, optical random access memory (RAM) and encryption. A scheme to generate return-to-zero on-off keying (RZ-OOK) high speed all-optical pseudo random bit sequence (PRBS) using binary phase shift keyed (BPSK) signal based on quantum-dot semiconductor optical amplifiers (QD-SOA) has been designed and studied. The PRBS is generated by a linear feedback shift register (LFSR) composed of all-optical logic XOR and AND gates. Generation of other Boolean logic operation using BPSK signals will be described. The XOR gate is composed of a pair of QD SOA Mach-Zehnder interferometers, which can generate BSPK signal to realize all-optical logic XOR gate. Results show that this scheme can mitigate the pattern effects and increase the operation speed to ~250Gb/s. For devices with relaxation time ~1.0ps, injected current density>1.5kA/cm2, signal pulse energy around 0.5pJ~1.0pJ with pulse width around 1.0ps, the system is capable of PRBS generation at speeds of ~250Gb/s with good output quality.

9202-25, Session 5

Remote fluorescence lifetime inspection of hermeticity of packaged food containers

Edgar A. Mendoza, Yan Esterkin, Connie Kempen, Sunjian Sun, Redondo Optics, Inc. (United States)

This paper describes recent progress towards the development of a remote “frequency-domain” fluorescence lifetime (SeePhase™) monitor used for the real time hermetic seal leak inspection of packaged food containers. A multitude of food goods, meets, vegetables, and beverages are typically packaged within an inert environment to reduce the risk of bacteria growth and increase the storage life of the food product. The SeePhase™ system uses a multi-parameter oxygen, carbon dioxide, and moisture sensitive patch that is placed within the hermetic sealed food package. Upon the presence of gases oxygen, carbon dioxide, or moisture inside the hermetic sealed food package, the sensor patch produces a fluorescence lifetime signature characteristic of a hermetic seal leak damage of the package.

The SeePhase™ system uses a miniature fluorescence lifetime monitor device to remotely detect the environmental status of the multi-parameter sensor patch with microsecond response times suitable for monitoring the food-packaged environment while in production, transit, or storage. The SeePhase™ hermetic seal leak detection sensor patch has applications in the food industry, aerospace (environments that required hermetic seal), consumer good, pharmaceuticals, chemicals, military (specialized equipment, harsh environments, highly explosive areas), scientific research equipment, and clean rooms.

9202-26, Session 6

Utilizing self-seeding RSOA with Faraday rotator mirror for colorless access network

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Recently, using self-seeding RSOA mechanism with 1.25 and 2.5 Gbit/s on-off keying (OOK) modulation format has been proposed to act as the wavelength-tunable laser for wavelength-division-multiplexing passive-optical-network (WDM-PON). In this paper, we propose and demonstrate a self-seeding RSOA-based laser by employing 3.43 Gbit/s orthogonal-frequency-division-multiplexing quadrature-amplitude-modulation (OFDM-QAM) with bit-loading for upstream traffic in colorless WDM-PON. A Faraday rotator mirror (FRM) is used to produce self-seeding operation.

In this measurement, the wavelength-tuning range of the proposed RSOA-based laser is obtained at whole C-band (1530.0 to 1565.0 nm). The measured output powers and optical signal to noise ratios (OSNRs) are -8.02 to -4.73 dBm and 60.3 to 67.49 dB, respectively, when the RSOA is operated at 70 mA. To achieve 3.43 Gbit/s traffic date rate, an OFDM-QAM modulation with bit-loading method is applied on proposed self-seeding RSOA laser. After 20 km single-mode fiber (SMF) transmission, the measured bit error rate (BER) is less than 3.8?10^-3 [forward error correction (FEC) threshold] at the 1550.0 nm wavelength. Besides, we also can retrieve a negative power penalty of 5.26 dB after 20 km SMF transmission while the RSOA is set at 70 mA.

Finally, we also compare and investigate the signal performance by using a polarization-insensitive fiber mirror (FM) as a light reflector instead of the FRM. Experimental results show that the stability and BER performance of the FM-based laser is worse than that of using FRM.

9202-27, Session 6

Demonstration of 2.5 Gbit/sec free space optical communication by using Y-00 cipher - toward secure aviation systems -

Fumio Futami, Osamu Hirota, Tamagawa Univ. (Japan)

Today, information of the optical communication includes lots of confidential data like company secret information and personal information. Therefore, a leakage of confidential data from optical communication channel may cause a serious damage. For an eavesdropper who tries to eavesdrop confidential data, the mathematical cipher is currently employed. However, the cipher break history shows such mathematical cipher is not reliable enough. Such fact demands development of more reliable cipher and drives us to focus actively on the research and development of Y-00 cipher. Y-00 cipher is an encryption scheme combined with physical phenomena and mathematical cipher, and it provides high speed performance and a provable security. It features to employ multi-level signal to block reading ciphertext by an eavesdropper. So far, the authors have focused mainly on the application of Y-00 cipher to the optical fiber transmission for protecting optical transport layer from eavesdropping. However, wireless communication of aviation contains also high capacity confidential information and therefore such communication requires secure high speed data communication scheme by using reliable cipher. In this report, for the first time to our knowledge, the authors propose free space optical communication by utilizing intensity-modulated Y-00 cipher for secure aviation systems including unmanned aircraft systems. Y-00 cipher transmitter and receiver with intensity levels of 4096 at data rate of 2.5 Gbit/s are fabricated for free space optical communication and an experiment of free space Y-00 cipher optical communication is successfully demonstrated.

9202-28, Session 6

All optical two-way time transfer in strongly heterogeneous networks

Josef Vojtech, Vladimir Smotlacha, Jan Radil, CESNET z.s.p.o. (Czech Republic)

Time and frequency transfer is standard task of time metrology. For instance the realization of UTC time scale is based on comparison of several hundred atomic clocks distributed in many countries. The traditional method of time transfer is a dedicated two-way satellite transfer link or utilization of global navigation system (e.g. GPS). The first mentioned method excels in accuracy but is very expensive as requires dedicate channel in geostationary satellite. Optical transfer over fiber link can provide even better accuracy and stability and is subject of intensive research. In this contribution we continue with description of verified time transmission implementations over significantly heterogeneous optical infrastructure. In past we presented time transmission over pair of unidirectional alien wavelengths to the distance of 550 km. They were established in DWDM transmission systems, commercial and combination of commercial and open system. The reached time transfer accuracy in term of TDEV was 30 ps over the averaging interval of 100 s. Further we reported the usage of bidirectional passive dark channel established inside amplified single fiber DWDM transmission system. Measured results shown the potential for better time transmission stability. The contribution will deal with the extension of this approach: the time transmission through amplified bidirectional channel established in single fiber within the combination of passive CWDM system and amplified DWDM system.

9202-29, Session 6

Fiber optic sensor for vibration detection

Nicolas Javahiraly, Ayoub Chakari, Univ. of Strasbourg (France)

We propose a polarimetric fiber optic vibration sensor that includes the study of the variation of the dephasage as a function curve radius (of the standard fiber optic) with and without the intrinsic birefringence.

The principle is based on the evolution of polarization when the constraint (vibration) is applied on a sensitive zone of the sensor.

We study the effects of a vibration application on our home made system (with a continuous frequency) and the polarisation evolution on the Poincaré sphere.

The study has demonstrated a very good accuracy and a good agreement between the theoritical and the experimental results was achieved.

9202-30, Session 7

An order of magnitude improvement in optical fiber bandwidth using spatial domain multiplexing/space division multiplexing (SDM) in conjunction with orbital angular momentum (OAM) *(Invited Paper)*

Syed H. Murshid, Saud Alanzi, Arnob Hridoy, Gregory L Lovell, Florida Institute of Technology (United States); Gurinder S. Parhar, Abhijit Chakravarty, EMCORE Corp. (United States); Bilas Chowdhury, Florida Institute of Technology (United States)

A novel MIMO multiplexing technique known as Spatial Domain Multiplexing/Space Division Multiplexing (SDM) can increase the bandwidth of existing and futuristic optical fibers by an order of magnitude or more. In the SDM technique, we launch multiple single mode pigtail laser sources of same wavelength into a carrier fiber at different angles. The launching angles decide the output of the carrier fiber by allocating separate spatial locations for each channel. Each channel follows a helical trajectory while traversing the length of the carrier fiber, thereby allowing spatial reuse of optical frequencies. In this endeavor we launch light from five different single mode pigtail laser sources at different angles (with respect to the axis of the carrier fiber) into the carrier fiber. Owing to helical propagation we get five distinct concentric donut shaped rings with negligible crosstalk at the output end of the fiber. These SDM channels also exhibit Orbital Angular Momentum (OAM), thereby adding an extra degree of photon freedom. We present the experimental data of five spatially multiplexed channels and compare them with simulated results to show that this technique can potentially improve the data capacity of optical fibers by an order of magnitude: A factor of five using SDM and another factor of two using OAM.

9202-31, Session 7

Development and deployment of a cavity enhanced UV-LED spectrometer for measurements of atmospheric HONO and NO2 in Hong Kong

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We report on the development of an analytical instrument based on incoherent broadband cavity enhanced absorption spectroscopy (IBBCEAS) for simultaneous measurements of HONO and NO2 in ambient air. Using a UV light emitting diode (LED) operating at ~ 366 nm in combination with a high finesse optical cavity having an effective optical path length of ~ 2.1 km, detection limits (for SNR=1) of 0.3 ppbv for HONO and 1 ppbv for NO2 were achieved with an optimum acquisition time of 120 s. The instrument performance was tested during a field campaign at a sub-urban site (Tung Chung) of ~7 days in Hong Kong. Excellent agreement in quantitative assessment of NO2 was obtained between the IBBCEAS instrument and a blue light convertor-based NOx analyzer during the campaign. Good agreement in absolute HONO concentration acquired by the IBBCEAS and a LOPAP (long path absorption photometer) has been observed. The present work performed in a real atmospheric environment demonstrates the feasibility of using IBBCEAS technique for interference (chemical and spectral) free measurement of HONO.

Experimental detail will be presented, the problems encountered by the IBBCEAS technique applied to the field observation and the further improvement will be discussed.

9202-32, Session 7

Analysis of dispersion compensation all-pass filter using micro-ring resonators

Ajay Kumar, Santosh Kumar, Indian School of Mines (India)

The Group delay time property is one of the most essential parameter, which is required to study and analyze. It is interesting to analyze the group delay time property of the multi-stage ring resonator all-pass filters in both the cascading single stages and using the lattice architecture. However, these properties has been studied, but it is restricted to directional couplers and waveguide characterized by the different parameters. The appropriate design of these parameters optimize the the group delay responses. Each single stage ring-resonator generates some extra phase shift. The generated extra phase shift can be adjusted to provide the broad-band group-delay. As the number of filter stages increases, we can obtain the larger bandwidth over the dispersion. Hence, the proposed device is able to provide the dispersion compensation in the various dense wavelength division multiplexer for the optical fiber communication system.

9202-33, Session 7

Ranging light sensing guide with periodic structure

Philipp G. Kornreich, Syracuse Univ. (United States)

In previous publications1,2,3,4 we performed a thorough analysis of an electronic camera that can measure the distance from each pixel to the point of the object that is in focus at the pixel. The camera used uniform Light Guide posts that detect light all along their length, Light Sensing Guides (LSG). Here the passive range measuring capability of a LSG with a periodic structure is analyzed. The LSG with a periodic structure has a superior range measuring capability. Ranging requires two components a convex lens and a LSG. This devices uses partially coherent broad band ambient light. A coherent light packet radiating from an object point has a length of only a few μm. Light packets radiating from an object point passing through the lens add constructively in the focal plane only at the point where this object point is in focus. Light from all other object points cancels. Each light wave in a light packet has a phase proportional to the distance the light packet traveled from the object point to the image point. In each light packet traveling in the LSG light is scattered by periodic structure from the forward traveling light wave. The scattered light forms a reverse traveling wave in the light packet. Thus the forward traveling wave looses amplitude. The reverse traveling wave increases in amplitude in the reverse direction in the light packet. This light pattern shifts in response to the phase of the incoming wave. Many light packets are simultaneously traveling through the LSG. The light does not interfere coherently between light packets. Light is detected all along the LSG. The detected signal depends on the total light power along the LSG. Since the light patterns shift the same way in each light packet in response to the phase of the light from the object point this detected signal has range information. The detected signal can be a photocurrent in one of the layers forming the periodic structure. An alternative detection method is to detect the photo voltage of p – n junctions in one type of the layer forming the periodic structure.

9202-34, Session 7

Real-time atmospheric imaging and processing with hybrid adaptive optics and hardware accelerated lucky-region fusion (LRF) algorithm

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Atmospheric turbulences can significantly deteriorate the performance of long-range conventional imaging systems and create difficulties for target identification and recognition. Our in-house developed adaptive optics (AO) system, which contains high-performance deformable mirrors (DMs) and the fast stochastic parallel gradient decent (SPGD) control mechanism, allows effective compensation of such turbulence-induced wavefront aberrations and result in significant improvement on the image quality. In addition, we developed advanced digital synthetic imaging and processing technique, "lucky-region" fusion (LRF), to mitigate the image degradation over large field-of-view (FOV). The LRF algorithm extracts sharp regions from each image obtained from a series of short exposure frames and fuses them into a final improved image. We further implemented such algorithm into a VIRTEX-7 field programmable gate array (FPGA) and achieved real-time video processing. We will present these experimental results for combining both AO and hardware implemented LRF processing technique over a near-horizontal 2.3km atmospheric propagation path. Our approach can also generate a universal real-time imaging and processing system with a general camera link input, a user controller interface, and a DVI video output.

9202-35, Session 8

LPFG sensing model for distributed shape control *(Invited Paper)*

Abraham K. Ishihara, Shahar Ben-Menahem, Carnegie Mellon Silicon Valley (United States); Alex A. Kazemi, The Boeing Co. (United States); Bernard Kress, Mykola Kulishov, USI Photonics Inc (United States)

We present an integrated model of an embedded LPFG (Long Period Fiber Grating) sensing network to measure bending and torsion of a

flexible wing. Driven by the need to improve aerodynamic efficiency and reduce fuel burn, interest in light-weight structures for next generation aircraft has been on the rise. However, in order to fully exploit novel lightweight structures, there is a critical need for distributed sensing along the entire wing span. Distributed parameter control algorithms can then leverage this information to stabilize the aircraft while modifying the wing shape.

LPFGs transmittance spectra are not only sensitive to both local bending and torsion of the wing at the grating locations, but at least four distinct real metrics (per grating location) can be extracted from such a spectrum for a single fiber (sensor string). These metrics have different — and in general pairwise linearly independent vectors of response coefficients. Furthermore, these response coefficients can be varied by using different periods at different gratings (which are optically connected in series along any given wing-spanning fiber). For these reasons, bending moment and torsion at a fiber's LPFG sensors can be robustly extracted from that fiber's transmittance spectrum. These measurements (or, indeed, similar ones with non-optical strain meters), can be used in conjunction with the elasticity equations, to reconstruct estimators for the state of the wing (instantaneous torsion and bending distributions along the wing). A model of an LPFG sensor string embedded in an Euler-Bernoulli beam is proposed along with an associated control algorithm.

9202-36, Session 8

Analysis of an all optical de-multiplexer architecture utilizing bevel design for spatially multiplexed optical fiber communication systems

Syed H. Murshid, Michael F. Finch, Gregory L. Lovell, Florida Institute of Technology (United States)

Spatial domain multiplexing (SDM) is a system that allows multiple channels of light to traverse a single fiber, utilizing separate spatial regions inside the carrier fiber, thereby applying a new degree of photon freedom for optical fiber communications. These channels follow a helical pattern, the screen projection of which is viewable as concentric rings at the output end of the system. The MIMO nature of the SDM system implies that a typical pin-diode or APD will be unable to distinguish between these channels, as the diode will interpret the combination of the SDM signals from all channels as a single signal. As such, spatial de-multiplexing methods must be introduced to properly detect the SDM based MIMO signals. One such method utilizes a fiber consisting of multiple, concentric, hollow core fibers to route each channel independently and thereby de-mux the signal into separate fibers or detectors. These de-mux fibers consist of the hollow core cylindrical structures with beveled edges on one side that gradually taper to route the circular, ring type, output energy patterns into a spot with the highest possible efficiency. This paper analyzes the beveled edge by varying its length and analyzing the total output power for each predetermined length allowing us to simulate ideal bevel length to minimize both system losses as well as total de-mux footprint. OptiBPM simulation engine is employed for these analyses.

9202-37, Session 8

Analysis of spatial domain multiplexing/ space division multiplexing (SDM) based hybrid architectures operating in tandem with wavelength division multiplexing

Syed H. Murshid, Gregory L Lovell, Bilas Chowdhury, Arnob Hridoy, Florida Institute of Technology (United States); Gurinder S Parhar, Abhijit Chakravarty, EMCORE Corp. (United States); Saud Alanzi, Florida Institute of Technology (United States)

Spatial domain multiplexing (SDM) also known as space division multiplexing adds a new degree of photon freedom to optical fiber multiplexing techniques by allocating separate radial locations to different MIMO channels as a function of the input launch angle. These independent MIMO channels remain confined to the designated location while traversing the length of the fiber, due to helical propagation of light inside the fiber core. The SDM technique can be used in tandem with other multiplexing techniques, such as time division multiplexing and wavelength division multiplexing in hybrid optical communication schemes, to achieve higher optical fiber bandwidth by increasing the photon efficiency due to added degrees of photon freedom. This paper presents the feasibility of hybrid optical fiber communications architecture and shows that SDM channels of different operating wavelengths continue to follow the input launch angle based radial distribution pattern.

9202-38, Session 8

Rollable nano-etched diffractive low-concentration PV sheets for space applications

Abraham K. Ishihara, Vincent Brac de la Pierriere, Shahar Ben-Menahem, Bernard C. Kress, Carnegie Mellon Silicon Valley (United States); Gregory A. Dorais, Kalmanje Krishnakumar, NASA Ames Research Ctr. (United States)

This paper discusses the design and fabrication of a prototype of a novel, rollable, mass fabricable, low-concentration photovoltaic sheet for space solar applications. The wrap consists of three thin (of order a millimeter or less), cheap plastic-sheet layers, which can be rolled together in a spiral wrapping configuration when stowed. Preliminary simulation based on the above modeling approaches show that the designs achieve comparable photovoltaic power (area for area) and (b) result in a flat angular response curve which remains flat from normal incidence of over 35 degrees to the normal. The simulations were performed using a ray tracing simulator built in Matlab. We discuss the construction of a demonstrator using quartz wafers based on the optimized design to show the technology. The main constraint for the fabrication of digital optical elements is the smallest dimension that can be etched on the wafer known as the critical dimension (CD). The CD strongly affect the performance of our system as it sets the maximum angle that can be deflected by each of our diffractive elements (layer 1 and 2). As a smaller CD commonly goes with an increase in the fabrication costs, the performances of the demonstrator we built were impacted by the choice of a relatively low cost fabrication. We designed the demonstrator's dimensions around this manufacturing constraint, and the associated maximum angle of deflection reachable by the diffractive layers. Details of its fabrication are presented and plans for further testing are provided.

9202-39, Session 8

Harsh environment fiber optic connectors/ testing

Douglas A. Parker, Esterline Connection Technology (United States) and Souriau USA, Inc. (United States)

Fiber optic systems are used frequently in military, aerospace and commercial aviation programs. There is a long history of implementing fiber optic data transfer for aircraft control, for harsh environment use in local area networks and more recently for in-flight entertainment systems. The advantages of fiber optics include high data rate capacity, low weight, immunity to EMI/RFI, and security from signal tapping. Technicians must be trained to install and maintain fiber systems, but it is not necessarily more difficult than wire systems.

However, the testing of the fiber optic interconnection system must be conducted in a standardized manner to assure proper performance. Testing can be conducted with slight differences in the set-up and procedure that produce significantly different test results.

This paper reviews various options of interconnect configurations and

discusses how these options can affect the performance, maintenance required and longevity of a fiber optic system, depending on the environment. Proper test methods are discussed. There is a review of the impact of changing such test parameters as input launch conditions, wavelength considerations, power meter options and the basic methods of testing. This becomes important right from the start when the supplier test data differs from the user's data check upon receiving the product. It also is important in periodic testing. Properly conducting the fiber optic testing will eliminate confusion and produce meaningful test results for a given harsh environment application.

9202-40, Session 8

Multi-spectral pyrometer for gas turbine blade temperature measurement

Shan Gao, Lixin Wang, Harbin Institute of Technology (China); Chi Feng, Harbin Engineering Univ. (China)

It is advantageous to operate the thermodynamic cycle of gas turbine at a high turbine inlet temperature , in order to achieve peak cycle efficiency and thus lower specific fuel consumption, for the mainly limits in the turbine blades temperature. Thus, achieving the highest possible turbine inlet temperature requires accurate knowledge of the turbine blade temperatures, as frequent excursions beyond the design limits of the blades can seriously reduce the service life. The problem for the accuracy of the temperature measurement includes the value of the target surface emissivity is unknown and the emissivity model is variability and the thermal radiation of the high temperature environment. The multi-spectral pyrometer designed provided mainly for range 500-1000 ?, and in this temperature range, the signal is much weaker than the high temperature, the SNR is lower and directly affect the accuracy of measurement. In this paper we present a model corrected in terms of the error due to the reflected radiation only on the basis of the turbine's known geometry and the physical properties of the material. Under different operating conditions, the method can reduce the measurement error from the reflect radiation of vanes, make measurement closer to the actual temperature of the blade and calculating the corresponding model through genetic algorithm. The experiment shows that this method has higher accuracy measurements.

9202-41, Session 9

Micro packaging of hermetic seal mini dual in line laser diode module for aerospace applications *(Invited Paper)*

Alex A. Kazemi, The Boeing Co. (United States); Eric Y. Chan, Dennis G. Koshinz, Boeing Research and Technology (United States)

Normally, reliable, reproducible, high-yield packaging technologies are essential for meeting the cost, performance, and service objectives for the harsh environment of space applications. This paper describes a new improved micro packaging method of hermetic seal mini-DIL (dual in line) laser diode module. The problem of using a softer solder resulted in failure mechanisms observed in the mini-DIL laser diode module based laser firing unit (LFU) for ordinance ignition of a missile system. These failures included: (1) failure in light output pulse power, (2) fiber pigtail damage inside the package snout which caused low LFU production yield. Our distinctive challenge for this project is the micro packaging of mini-DIL. For this package a new technique for the hermetic sealing using a patented micro-soldering process was developed. The process is able to confine the solder seal to a small region inside the snout near the fiber feed-through hole on the wall of the mini-DIL package. After completing the development, which included temperature and thermal cycling, X-rays analysis showed the new method had no fiber damage after the micro-soldering seal. The new process resulted in 100% success in the packaging design and we were granted a patent for the innovative development.

9202-43, Session 9

Making hexagonal electrodes on Nafion for deformable mirrors applications

Po-Jung Huang, Guo-Dung Su, National Taiwan Univ. (Taiwan)

In this paper, a fabrication of IPMC (Ionic Polymer Metal Composites) films with hexagonal electrodes for deformable mirrors applications has been described. With the array of hexagonal electrodes on one side of IPMC membrane, we can control the contour of IPMC by driving voltage selectively. Our fabrication process involves ion-exchange, lithography, and electroless plating steps. A positive photoresist in photolithography is used as the mask in the electroless plating process to selectively grow platinum electrodes in IPMC regions. We have measured the surface resistance of the IPMC. The surface resistance of the hexagonal electrodes is about 5?, which is small enough to enable the IPMC to be actuated by low voltage. The other side of the IPMC membrane is smooth and can be used as reflection surface. We have generated deformation on our IPMCs (3 cm X 3 cm) under a low actuation voltage less than 5 volts successfully. The maximum stroke of the IPMC deformable mirror is 15 um. Due to the low driving voltage of IPMCs, the deformable mirrors made of IPMCs is promising.

9202-44, Session 9

Mode splitting and resonant coupling between a slot metasurface and PMMA

Michael F. Finch, Brian A. Lail, Florida Institute of Technology (United States)

A slot metasurface (metascreen) designed to have resonance that couples with the 1733 cm-1 absorption peak of the C=O molecular bond of PMMA (polymethyl methacrylate) is presented. The metasurface is made of a gold layer perforated with periodically-placed slots and stood off above a reflective ground plane with silicon substrate. The metasurface is modeled using ANSYS HFSS and including measured optical properties for gold, silicon and PMMA in the infrared spectrum. PMMA forms a thin overcoat and exhibits a strong absorption resonance at wavenumber 1733 cm-1. Coupling between the metasurface and PMMA is observed via normal mode splitting. Mode splitting has been analyzed from classical coupled mass spring oscillators to exciton-photons coupling in microcavities. The coupled systems can be described with a Hamiltonian matrix and solved for the eigenfrequencies. Parametric analysis of coupled response as a function of the design geometry is provided. Coupling energy, reflectance spectrum, and dispersion plots showing the anticrossing behavior of hybrid modes are presented as characterization of resonance coupling and normal mode splitting. Slot metasurface results are compared to the complementary structure (nanorod metasurface) in order to explore the duality of the complentary metasurfaces and their coupled responses. Coupled resonances have application in biosensors for molecule detection, surface-enhanced infrared absorption (SEIRA), and infrared imaging.

9202-45, Session 9

Supercontinuum generation in tapered rib waveguide

Hongyu Hu, Wenbo Li, Niloy K. Dutta, Univ. of Connecticut (United States)

We have designed a tapered rib waveguide and numerically studied the generation of supercontinuum using such waveguides. The Air-SF57 glass-SiO2 waveguide is 3 cm long, with a varying etched depth to manage the total dispersion. Numerical simulations are conducted for input pulses at a wavelength of 1550 nm with a width of 150 fs and peak power of 5 kW. The proposed waveguide geometry greatly broadens the output spectrum, extending from ~1000 nm to ~ 6000 nm, caused

by the continuous modification of the phase matching condition for the generated waves. The coherence property has also been investigated, demonstrating that fully coherent supercontinuum extending from ~ 1000 nm to ~ 6000 nm can be obtained with proper pumping conditions. Optical pulses of width ~200 fs have been generated using optical fiber nonlinearities.

9202-67, Session 9

Concentric circles based simple optical landing aid for vertical takeoff and landing aircrafts

Syed H. Murshid, Gregory L. Lovell, Rayan Enaya, Florida Institute of Technology (United States)

Vertical takeoff and landing (VTOL) aircrafts such as helicopters and drones, add a flexible degree of operation to airborne vehicles. In order to operate these devices in low light situations, where it is difficult to determine slope of the landing surface, a lightweight and standalone device is proposed here. This small optical device can be easily integrated into current VTOL systems. An optical projector consisting of low power, light weight, solid state laser along with minimal optics is utilized to illuminate the landing surface with donut shaped circles and coaxial centralized dot. This device can placed anywhere on the aircraft and a properly placed fiber system can be used to illuminate the surface beneath the bottom of the VTOL aircraft in a fashion that during operation, when the aircraft is parallel to the landing surface, the radius between the central dot and outer ring(s) are equidistant for the entire circumference; however, when there the landing surface of the VTOL aircraft is not parallel to the landing strip, the radial distance between two opposite sides of the circle and central dot will be unequal. The larger this distortion, the greater the difference between the opposite sides of the circle. Visual confirmation or other optical devices can be used to determine relative alignment of the projector output allowing the pilot to make proper adjustments as they approach the landing surface to ensure safe landings. Simulated and experimental results from a prototype optical projector are presented here.

9202-47, Session 10

Rugged sensor window materials for harsh environments *(Invited Paper)*

Shyam S. Bayya, Guillermo Villalobos, Woohong R. Kim, Jas S. Sanghera, U.S. Naval Research Lab. (United States); Ishwar D. Aggarwal, Sotera Defense Solutions, Inc. (United States)

There are several DoD or commercial systems operating in very harsh environments that require rugged windows. On some of these systems, windows become the single point of failure. These applications include sensor or imaging systems, high energy laser weapon systems, submarine photonic mast, IR countermeasures and missiles. Based on the sea or land or air application the windows or domes on these systems must withstand wave slap, underwater or ground based explosions, or survive flight through heavy rain and sand storms while maintaining good optical transmission in the desired wavelength range. Some of these applications still use softer ZnS or fused silica windows because of lack of availability of rugged materials in shapes or sized required. There have been recent developments in rugged spinel, ALON and sapphire materials improving their optical transmission in 0.2 – 5.0 µm wavelength range. These rugged materials also have significantly higher strength and high thermal conductivity for high speed applications. Properties of these rugged materials and some recent advancements will be discussed at this meeting.

9202-48, Session 10

Circular polarized leaky wave surface

Franklin Manene, Brian A. Lail, Florida Institute of Technology (United States); Edward C. Kinzel, Missouri Univ. of Science and Technology (United States)

A circular polarized (CP) infrared (IR) leaky wave surface design is presented. The metasurface consists of an array of rectangular patches connected by microstrip and operating over the long-wave infrared (LWIR) specturm with directional wave emission and absorption. The surface is composed of arrays of sub-wavelength metal patches periodically aligned over a grounded dielectric slab. The design combines the features of the conventional patch and leaky wave antenna leading to a metasurface that preferentially emits CP IR radiation by use of axial asymmetrical unit cells. This is a deviation from reported structures that mainly employ a phase shifter to combine linearly polarized waves in order to attain circular polarization. The performance of this leaky wave surface is verified through full-wave simulation using the Ansys HFSS finite element analysis tool. Leaky phenomena is demonstrated by frequency scanning within the desired spectral range while CP is shown by the axial ratio of < 3dB. The main beam of this surface can be steered continuously by varying the frequency while maintaining a low axial ratio (below 3 dB) within the main beam direction. A CP leaky wave at 10.6?m with a scanning angle of 30 deg is demonstrated. Metasurfaces exhibiting spectral and polarization selectivity in absorption/emission hold the potential for impact in IR applications including detection, imaging, and tagging.

9202-49, Session 10

Analysis of LPFG sensor systems for aircraft wing drag optimization

Alex A. Kazemi, ARK International (United States); Abe Ishihara, Carnegie Mellon Univ. (United States)

In normal fiber, the refractive indices of the core and cladding do not change along the length of the fiber; however, by inducing a periodic modulation of refractive index along the length in the core of the optical fiber, the optical fiber grating is produced. This exhibits very interesting spectral properties and for this reason we propose to develop and integrate a distributed sensor network based on long period fiber gratings (LPFGs) technology which has grating periods on the order of 100 µm to 1 mm to be embedded in the wing section of aircraft to measure bending and torsion in real-time in order to measure wing deformation of commercial airplanes resulting in substantial benefits such as reduced structural weight, mitigation of induced drag and lower fuel consumption which is fifty percent of total cost of operation for airline industry.

Fiber optic sensors measurement capabilities are as vital as they are for other sensing technologies, but optical measurements differ in important ways. In this paper we focus on the testing and aviation requirements for LPFG sensors. We discuss the bases of aviation standards for fiber optic sensor measurements, and the quantities that are measured.

Our main objective is to optimize the design for material, mechanical, optical and environmental requirements. We discuss the analysis and evaluation of extensive testing of LPFG sensor systems such as attenuation, environmental, humidity, fluid immersion, temperature cycling, aging, smoke, flammability, impact resistance, flexure endurance, tensile, vitiation and shock.

9202-50, Session 10

Modeling and Optimization of a Novel Diffractive Low Concentration PhotoVoltaic (LCPV) Design

Abraham K. Ishihara, Carnegie Mellon Silicon Valley (United

States); Shahar Ben-Menahem, Carnegie Mellon University (United States) and Carnegie Mellon Silicon Valley (United States)

In this paper we discuss the modeling and optimization aspects of a novel LCPV design termed MOUND-PV ("Multilayer Optimal Uniformity Nanomachined Diffractive " cellular PV wrap). Each repeating MOUND cell is uniaxial, having several (at least two) diffractive layers above a high-aspect-ratio (but otherwise standard) rectangular PV cell. The top optical layer of each cell, is in essence a Fresnel lens. Each layer consists of a thin dielectric slab, etched or embossed with a quasi-periodic groove pattern. Two MOUND design versions are reported and discussed: (1) analogue sawtooth (blazed, triangular-prism grooves); (2) discrete multi-level grooves. In either case, the critical dimensions of some cell grooves may be sub-wavelength. Each design version is associated with a number of optimizable parameters, both continuous and discrete, impacting performance metrics as diffractive efficiency modulation and acceptance angle. In addition, constraints imposed due to manufacturing consideration are discussed. In each design version, we discuss the interaction of the optical transfer function (OTF) with the electrics and thermodynamics of the cell array. In particular, we model non-uniformities in illumination and groove geometry, and their adverse effects upon cell efficiency and reliability. Finally, performance of MOUND cell arrays is compared to that of a standard PV flat panel, with both utilizing the identical mono-crystalline PV material. Metrics including optical and PV efficiencies, thermal variability, and acceptance angle, are reported.

9202-52, Session 11

A displacement and rotation sensor for spatial and rough conditions of use, based on micro polarimetric imaging

Francis Georges, Univ. de Strasbourg (France); Mustapha Remouche, Volumion Company Strasbourg (France); Patrick Meyrueis, Univ. de Strasbourg (France)

It is well known that by rotating a polarizer illuminated by a polarized light source we are going to obtain a light intensity modulation that will be related to the rotation of the polarizer. This phenomena was very difficult to exploit for high accuracy rotation measurements because some sub phenomena induce noises in the measurements that stay in this way in the low accuracy domain.

We have elaborated a method a process and an engineering process that allow to obtain a high accuracy repetitive measurement that can be efficient in poor condition like low or high temperature, vibration, moisture, etc.

All these advantages can be obtained at low cost for embarkable product.

The polarisers can be low quality as well as the light source as the light sensor. These results are obtained by a specific analysis of the photonics signal encoding of the response of the device.

On this bases we have developed validation prototypes that can operate in rough conditions with good results.

We describe the principles the design of the proposed device, we compare the modeling and the experimental results. We discuss the output of this comparison and we describe what could be the industrial continuation of our theoretical and experimental results including miniaturization and mass production including the ecologic footprint compared to specifications of other kinds of optical displacement and rotation sensors.

9202-53, Session 11

Nanomaterial enabled evanescent wave absorption spectroscopy based sensors for high temperature, harsh environment sensing

Michael P. Buric, Paul R. Ohodnicki Jr., National Energy Technology Lab. (United States); Benjamin Chorpening, National Energy Technology Lab (United States)

High temperature compatible harsh environment sensors can enable improved process control for higher-efficiency, lower emission power generation applications. Such sensors can also have broad impacts across an array of other industries and applications including nuclear power generation, aviation, aerospace, and industrial manufacturing. Optical based sensor platforms are attractive because they (1) eliminate many common failure modes of electrical based sensors such as the need for electrical wiring and interconnects at the sensing location, (2) reduce the risk of explosions due to an electrical spark when deployed in explosive atmospheres, and (3) allow for increased functionality due to compatibility with broadband wavelength interrogation and distributed sensing methodologies. Recent progress in development of nanomaterial enabled evanescent wave absorption spectroscopy-based sensors for extreme temperature applications will be presented from both an experimental and theoretical perspective. In particular, we will present new high temperature gas sensing results for sensors fabricated using a specifc class of doped metal oxide-based functional sensor materials that have been demonstrated to show enhanced optical sensing responses over a broad range of wavelengths as compared to base oxides. Experimental results will be presented at temperatures ranging from 300-700C and will be coupled with theoretical modeling of both materials and functionalized sensors to explain measured sensing responses in terms of an interaction between the sensor material and high temperature gas streams. Future research directions for improved materials and sensor development will be highlighted.

9202-54, Session 11

Pressure sensitivity analysis of fiber Bragg grating sensors

Nezih Mrad, Defence Research and Development Canada (Canada); Vasant Sridharan, Univ. of Waterloo (Canada); Alex Kazemi, The Boeing Co., Commercial Airplanes, (United States)

Recent development of fiber optic sensing technology has mainly focused on discrete sensing, particularly sensing systems with potential multiplexing and multi-parameter sensing capabilities. Bragg grating fiber optic sensors have emerged as the non-disputed champion in multiplexing and potential simultaneous dual parameter sensing (strain and temperature). These single-ended, highly multiplexed (up to hundreds of discrete sensors on a single fiber) sensors have a high potential for use in aerospace applications where conventional sensing technology is not suitable. Such applications include in-service health monitoring of composite structures, in-situ composite process monitoring, crack detection and monitoring, structural and acoustic vibration monitoring, bonded patch repair health assessment and monitoring, and impact damage detection and evaluation.

Although the number of potential applications for this sensing technology is large and spans the fields of medicine, automotive, aerospace, and infrastructure, critical issues such as fatigue life, sensitivity, accuracy, embeddability, and material/sensor interface integrity still need to be addressed. The purpose of this work is to enhance the understanding of this sensor technology through experimental evaluation of pressure measurement fiber Bragg grating sensors with two different coatings: Polymide and Acrylate and two different arrangements: Arrayed and Single. It is concluded that a fiber Bragg grating sensors are sensitive to pressure and that experimental sensitivity correlated well with that of the theory. Such results, suggests that pressure should be considered when using this instrumentation and measurement tool.

9202-55, Session 11

Direct B-integral measurement, and SPM compensation in fiber optic CPA systems

Sangyoun Gee, Michael M. Mielke, Raydiance, Inc. (United States)

B-integral of a fiber optic amplifier in the chirped pulse amplification (CPA) system is directly estimated by measuring the background free intensity autocorrelation of output pulses of a dual pulse input. For a pair of input pulses, the chirped nature of the amplification transforms a nonlinear phase change into an amplitude change which can be measured simply by second harmonic autocorrelation. This nonlinear amplitude distortion typically creates satellite pulses in addition to the original two pulses. The relative strength of the satellite pulses is directly related to the amount of the B-integral accumulated during the amplification. The input pulses were generated by a pulse shaper based on a diffraction grating and a liquid crystal on silicon (LCOS). This method can be used up to B-integral value of ~4 until the autocorrelation trace became too complicated to distinguish individual peaks. Using the same pulse shaper and taking advantage of the fact that the pulse is linearly chirped, SPM of the amplifier is compensated, which was confirmed by the same B-integral measurement method. This scheme is an effective nonlinearity management method for CPA system equipped with a pulse shaping element. Salient feature of this scheme is that this method provides a mean to compensate the SPM in amplifiers as well as a mean to measure the degree of nonlinearity compensation at their normal operating condition.

9202-56, Session 12

Single video camera method for using scene metrics to measure constrained 3D displacements

Leo R. Gauthier Jr., Melissa E. Jansen, John R. Meyer, Johns Hopkins Univ. Applied Physics Lab., LLC (United States)

There are numerous ways to use video cameras to measure 3D dynamic spatial displacements. When the scene geometry is unknown and the motion is unconstrained, two calibrated cameras are required. The data from both scenes are combined to perform the measurements using well known stereoscopic techniques. There are occasions where the measurement system can be simplified considerably while still providing a calibrated spatial measurement of a complex dynamic scene. For instance, if the sizes of objects in the scene are known a priori, these data may be used to provide scene specific spatial metrics to compute calibration coefficients. With this information, it is not necessary to calibrate the camera before use, nor is it necessary to precisely know the geometry between the camera and the scene. Field-of-view coverage and sufficient spatial and temporal resolution are the main camera requirements. Further simplification may be made if the 3D displacements of interest are small or constrained enough to allow for an accurate 2D projection of the spatial variables of interest. With proper camera orientation and scene marking, the apparent pixel movements can be expressed as a linear combination of the underlying spatial variables of interest. In many cases, a single camera may be used to perform complex 3D dynamic scene measurements. This paper will explain and illustrate a technique for using a single uncalibrated video camera to measure the 3D displacement of the end of a constrained rigid body subject to a perturbation.

9202-57, Session 12

Highly distributed multi-point, temperature and pressure compensated, fiber optic oxygen sensors (FOxSense) for aircraft fuel tank environmental and safety monitoring

Edgar A. Mendoza, Yan Esterkin, Connie Kempen, Sunjian Sun, Redondo Optics, Inc. (United States)

This paper describes recent progress towards the development and qualification of a highly distributed, multi-point, all optical pressure and temperature compensated, fiber optic oxygen sensor (FOxSense™) system for closed-loop monitoring and safety of the oxygen ullage environment inside the fuel tanks of military and commercial aircraft. The all-optical FOxSense™ system uses a passive, multi-parameter (O2/T&P) fiber optic sensor probe with no electrical connections leading to the sensors install within the fuel tanks of an aircraft. A highly integrated fluorescence lifetime optoelectronics system is used to interrogate the status of all the deployed sensors in real time.

The deployed (O2/T&P) fiber optic sensors install in the fuel tanks of the aircraft are connected to the FOxSense optoelectronic system via a MIL-SPEC fiber optic conduit. The all optical sensor consists of an integrated multi-parameter fiber optic sensor probe that integrates a fluorescence based optical oxygen optrode with built-in temperature and pressure optical sensors within the same probe for compensation of temperature and pressure variants induced in the fluorescence response of the oxygen optrode. A multichannel frequency-domain fiber optic sensor read-out (FOxSense™) system is used to interrogate the optical signal of all three sensors in real-time and to display the fuel tank oxygen environment suitable for aircraft status and alarm applications. Preliminary testing of the all optical fiber optic oxygen sensor have demonstrated the ability to monitor the oxygen environment inside a simulated fuel tank in the range of 0% O2 to 21% O2 concentrations, temperatures from (-) 40°C to (+) 60°C, and altitudes from 0-ft to 40,000-ft.

9202-58, Session 12

Fiber optic sensitizer coatings: materials and applications *(Invited Paper)*

Indu F. Saxena, Intelligent Optical Systems, Inc. (United States)

In order to achieve a high sensitivity, and maximize optical fiber response to transduce sufficiently into the properties of light propagating through the optical fiber for target variables, dedicated coatings have been developed, in addition to specialized detection techniques. Specific coatings, in particular polymers, metals and hermetic coatings, when applied to optical fibers have been shown to increase their sensitivity to desired parameters by at least an order of magnitude.

Sensitizer coating materials for increasing sensor responses to several physical and chemical parameters, including temperature and strain will be described and their performance enhancements discussed.

9202-59, Session 12

Highly reproducible Bragg grating acousto-ultrasonic contact transducers

Indu F. Saxena, Intelligent Optical Systems, Inc. (United States)

FIber optic acousto-ultrasonic transducers offer numerous applications as embedded sensors for impact and damage detection in industrial and aerospace applications as well as non-destructive evaluation. Superficial contact transducers with a sheet of fiber optic bragg gratings has been demonstrated for guided wave ultrasound based measurements. It is reported here that the measurement technique provides highly reproducible measurements of guided ultrasound in the test component, despite the optical fiber not being permanently embedded in the component under test.

9202-61, Session 12

Generation of dynamic Brillouin grating in polarization maintaining fiber

Dipankar Sengupta, Marco Santagiustina, Fabrizio Chiarello, Luca Palmieri, Univ. degli Studi di Padova (Italy)

We report an experimental demonstration of characterization of Dynamic Brillouin grating (DBG) in polarization maintaining fiber (PMF). In our scheme Vector network analyser is introduced to determine the

Brillouin frequency of the PMF. A moving acoustic grating is realized and generated by stimulated Brillouin scattering between two counter propagating optical waves (Pump wave and stokes wave) in one polarization, and used to reflect orthogonally polarized waves at different wavelength. The experimental results shows that frequency of the reflected wave from the grating is at 44 GHz from the stokes wave and is very close to the numerical calculation by a theoretical analysis. The paper also presents the acoustic grating characteristics property, length and reflectance.

9202-66, Session 12

Fiber optic connectors for harsh environment of aviation and aerospace applications

Alex A Kazemi, ARK International (United States)

Fiber optic connector technology is making significant advances for use in aviation and aerospace applications. This increasing user friendly system has contributed to more novel extremely small multi-fiber connectors for fiber optic interconnection. With low insertion loss and excellent environmental endurance to harsh environment they meet the requirements of higher integration in optical backplane.

Severe conditions, extreme surroundings, rough weather, rugged and unforgiving environment call for the use of high-performance fiber optic connectors. Appropriate connector selection is essential to assure adequate optical, environmental and mechanical performance. The selection of these items should be specific to the requirements of the system when considering environmental and mechanical limitations, and from the standpoint of the users who will be installing, maintaining and possibly repairing the system sometime in the future. Proper installation, maintenance and repair training is essential.

This paper outlines the attributes, environments, requirements, technologies and options of fiber optic connectors for harsh environment for aviation and aerospace applications. Furthermore, it describes various state-of-the-art technologies, particularly for aviation, aerospace applications. Discussion will also place emphasis on physical contact and expanded beam designs which are the fiber optic technologies being used in harsh environment of aviation and aerospace applications.

Conference 9203: Interferometry XVII: Techniques and Analysis

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9203-1, Session 1

Complete shape measurement of micro parts by digital holography

Silke Huferath-von Luepke, Reiner Klattenhoff, Colin Dankwart, Claas Falldorf, Ralf B. Bergmann, Bremer Institut für angewandte Strahltechnik GmbH (Germany)

Industry frequently demands the inline inspection of the full shape of produced components. Fast and robust measurement techniques are needed for detection of defect parts. We present a method for complete 360 degree measurement of the shape of a micro-cup using digital holographic microscopy. Digital holography is suitable to determine the shape of objects such as a micro-cup with a diameter of 1 mm and a height of about 600 µm due to its enhanced depth of focus. It is a fast method since data acquisition time can be in the nanosecond range. The lateral resolution of the set-up used here goes down to 700 nm. Due to the fact that the object is much larger than a few wavelengths we use two wavelengths contouring which defines the resolution in depth. We use a synthetic wavelength of 112 µm which yield to a depth resolution in the range of 3 µm. Due to the limited depth of field the micro-cup has to be numerically reconstructed in different depth. All reconstructed layers are merged to generate a sharp image of the micro-cup over its depth. This merging uses an autofocus algorithm based on the standard deviation of the reconstructed phase difference which results in a height map of the object. A 3D scatter plot is generated from this height map. Digital holograms captured from different directions are used by the program GEOMAGIC to generate a complete 360 degree scatter plot of the measured micro-cup.

9203-2, Session 1

Development of in-plane and out-of-plane deformation simultaneous measurement method for the analysis of buckling

Yasuhiko Arai, Kansai Univ. (Japan)

The deformation measurement method by using only two speckle pattern has been proposed in ESPI by using Fourier transform. Speckle interferometry can measure not only the out-of-plane but also the in-plane deformation measurement of the objects with rough surfaces. So, speckle interferometry is useful optical measurement method in the analysis of buckling phenomenon that occurs simultaneously in-plane and out-of-plane deformations in a beam. Generally, the in-plane deformation can be detected by using the two-beam speckle interferometer. At present, some methods of 3-D deformation measurements have been also reported using some special speckle interferometers based on two-beam interferometer. Then, Fourier transform and the technologies based on digital holography were employed there. In these reports, some sets of the two-beam speckle interferometer are combined for 3-D deformation measurement. However, there are some problems. In this paper, a novel in-plane and out-of-plane deformation measurement optical system is proposed by combining one pair of interferometers under the idea based on the principle of two-beam interferometer. Then, the optical system is applied to the analysis of the buckling phenomena. The availability of the proposed method in the analyzing process of buckling phenomenon is confirmed by discussing with Euler's buckling theory. From the experimental results, it can be confirmed that the buckling analysis of the beam agrees very well with the theory of Euler buckling. Because the proposed method can measure simultaneously and high precisely the in-plane and out-of-plane deformation, it can be confirmed that the proposed method is available for analyzing of the buckling phenomenon.

9203-3, Session 1

Real-time processing of off-axis interferograms: from the camera to the user

Pinhas Girshovitz, Tamir Gabai, Natan T. Shaked, Tel Aviv Univ. (Israel)

Digital holography captures the complex wave-front (amplitude and phase) of objects and it is useful for a wide range of applications. However, the use of digital holography typically involves off-line post-processing of the interferograms to the complex wave-front of the sample. This processing is done off-line due to the computational complexity of existing algorithms that allow processing time of approximately two frames per second (fps) per 1 megapixel interferograms. Here we present a new approach that significantly decreases the reconstruction time of the sample wave-front in off-axis interferometry without the need for previous knowledge about the sample structure. This is done by significantly reducing redundant calculations done by the conventional Fourier-based algorithm, making the reconstruction more efficient, while using a single-core processing unit on a standard personal computer. The presented implementation works without using advanced hardware to enable parallelization of the image data processing, as done with GPUs. The new approach is simply implemented on a Labview-Matlab environment, which allows a user-friendly interface. We show that using the new approach, we can reach a processing speed of above 30 fps for 1 megapixel interferograms, allowing for real-time visualization on standard processors.

9203-4, Session 1

Dual-wavelength digital holography: single shot calibration

Davood Khodadad, Per Bergström, Luleå Univ. of Technology (Sweden); Emil Hällstig, Optronic (Sweden); Mikael Sjödahl, Luleå Univ. of Technology (Sweden)

Phase ambiguity as an inherit limitation of dual-wavelength interferometry for shape measurement is a reason to use multi-wavelength methods. In an on line shape measurement in disturbed environment, use of many wavelengths may become a problem as it is necessary to acquire all holograms simultaneously due to environmental disturbances. It is therefore important to investigate alternative single shot approaches. This paper is a continuation of our work on single shot dual-wavelength shape evaluation using speckle displacements and regularization and allows single shot online shape measurement in the disturbed medium.

To make the shape data available for measurement they have to be extracted from a recorded image in spectral domain. Appropriate cut area and window size in the Fourier method are therefore of great importance for decoding information carried by different wavelengths. For this purpose a registration procedure is applied using correlation peak search to find the best cut area, window size and also match the central point of spectral frequencies of the image are used to extract the holograms. Furthermore using different laser sources, induces aberration and pseudo phase changes which must be compensated. To insure any phase change is only because of the object shape, calibration is therefore indispensable. In order to do the calibration, both holograms are numerically propagated to a focus plane to avoid any unknown errors. Deviations between a reference known plate and its measurement are found and used for calibration. The aim of the paper is to describe properties of the proposed method and relative results.

9203-5, Session 1

Transparent stepped phase measurement using two illuminating beams

Behnam Tayebi, Farnaz Sharif, Mohammad Reza Jafarfard?, Dug Young Kim, Yonsei Univ. (Korea, Republic of)

We propose a common path, off axes, single shot and single wavelength phase microscope technique for measuring high phase transparent objects without using unwrapping process. A grating between a laser and the object is used to make beams with different angle, which determines the measurement range of the microscope. The grating pitch and magnification of the lens system before the sample affect the angle. The angle inside the object is changed according to snell's law; therefore, final angle is related to the refractive index of the object. Magnification of the lens system after sample will control the modulation frequency of microscope. The interference pattern is constructed at CCD plane and convey information of the sample. For a phase below the measurement range of the microscope, the reconstructed phase is not wrapped. By increasing the measurement range accuracy of the system will drop; therefore the magnification of the lenses must choose carefully to obtain optimal phase. The ability of this technique is demonstrated by reconstructing phases of two transparent step objects with 150 and 510 micrometers height. Their refractive indexes for red light are 1.515 and 1.508 , respectively. Therefore, total optical path length difference is 336 micrometers that is 500 times more than the laser wavelength. The phase is successfully reconstructed without using unwrapping algorithms.

9203-6, Session 1

ITIA: tripling the field-of-view in off-axis interferometric phase microscopy

Irena Frenklach, Pinhas Girshovitz, Natan T. Shaked, Tel Aviv Univ. (Israel)

Interferometric phase microscopy (IPM) is a quantitative imaging method for capturing an interference pattern of the light interacting with a sample and a reference beam coming directly from the source. While being an invaluable tool for metrological,biological and medical research, most IPM setups are unfriendly for inexperienced users, and have limited field of view (FOV). To overcome the limited FOV problem, it is possible to scan the sample and record a wider FOV. However, dynamic samples might move by the time the scan is over. We present a new quantitative imaging technique, referred to as interferometry with tripled-imaging area (ITIA), which is capable of capturing three off-axis interferometric fields of view in a single camera exposure, thus tripling the acquired information without the need to scan, without decreasing the image resolution and without changing the system magnification. We used an inverted transmission microscope illuminated by a Helium-Neon laser with wavelength of 632.8nm. The sample is projected onto the image plane on the output of the inverted microscope, where the ITIA module is placed. In order to demonstrate our technique we used it to image optically transparent 1951 U.S. air force test target on a glass plate (made using a photolithography process of UV-cured adhesive), thin diatom shells and live human cancer cells.

9203-7, Session 2

Practical Fabry-Perot displacement interferometry in ambient air conditions with subnanometer accuracy *(Invited Paper)*

Dirk Voigt, Arthur S. van de Nes, Steven A. van den Berg, VSL Dutch Metrology Institute (Netherlands)

Displacement interferometry is an important tool for optical metrology in precision engineering and high-tech systems. The optical wavelength provides access to outstanding resolution. Fabry-Perot interferometry (FPI) is of particular interest for the validation and calibration of highest precision displacement sensors to sub-nanometer measurement uncertainty. Since the resonant optical frequency can be measured with very high accuracy and free of periodic nonlinearity, FPI allows for direct traceability to the time standard. In practice, however, it is challenging to establish sufficient thermo-mechanical and ambient climate stability to go beyond nanometer-level measurement uncertainty.

We report on the concept and status of implementation of a new, compact FPI setup. With a cavity length shorter than 1 mm, we aim for air refractive index fluctuations to be negligible at picometer-level uncertainty contribution. In order to establish the required large laser frequency tuning range (THz-scale free spectral range of the cavity), the use of a DFB diodelaser is investigated. Another benefit of the short cavity is the large frequency sensitivity to the actuated cavity mirror displacement. This allows for the use of a portable, calibrated wavemeter and eases traceability requirements.

Furthermore, we report on our methodology for mounting, alignment and calibration of capacitive displacement sensors as with respect to the actuated target electrode of our metrological FPI. This latter instrument is less compact (14 cm cavity) but equipped with a dedicated flexure mechanism for displacement strokes up to 300 micron.

9203-8, Session 2

Simultaneous determination of thickness and refractive indices of birefringent wafer by simple transmission measurement

Hee Joo Choi, Jun Yeol Ryu, Myoungsik Cha, Pusan National Univ. (Korea, Republic of)

We demonstrate a method for determination of the principal indices of refraction and the thickness of a birefringent wafer by simply measuring the light transmittance. The light transmittance was measured while rotating the wafer. The directly transmitted beam makes interference with those multiply reflected at the interfaces, producing an interferogram as a function of angle of incidence. The interferogram is that of a low-finesse Fabry-Pérot etalon, which gives several parameter pairs (index and thickness) unless the thickness of the plate is accurately known. In our previous work, we resolved this 2-pi phase ambiguity by using dual wavelengths input [Opt. Express 18, 9429 (2010)]. Here, we made use of the birefringence of the material instead of dual wavelengths, in order to resolve the ambiguity. For an experimental demonstration, we used an x-cut $LiNbO_3$ (LN) wafer. A single-mode laser beam passed through the LN wafer. Two interferograms were obtained for the two orthogonal polarizations. The analysis of each interferogram resulted in probable parameter pairs. Comparison of the two orthogonal interferograms gave a common thickness, which should be the correct value, thus determining the correct values of the ordinary (no) and extraordinary indices (ne) simultaneously. As a result, we determined no = 2.21192 and ne = 2.13832 (uncertainty10^-5) at 1529 nm for LN, which agree well with the known values [Edwards and Lawrence, Opt. Quantum Electron. 16, 373 (1984)]. We expect that this method can be useful for determining the principal refractive indices of newly-developed birefringent crystals with accuracy and simplicity.

9203-9, Session 2

Interferometric system for detecting radiation wavelength shift

Pavel Brazhnikov, Vasiliy Andrianov, Oleg Koltovoy, Alexander Tikhov, All-Russia Research Institute of Automatics (Russian Federation)

Interferometric measurement system based on the Fabry-Perot etalon, for precision wavelength measurements. The Fabry-Perot scheme has drawbacks such as light losses and the low accuracy of recording because of the not constant distance between interferometer mirrors.

Therefore an optical scheme was developed that direct more light onto the recorder. This optical scheme use cylinder lenses for create the light line and reduces spherical aberration effect . Eliminating of effect of mirror tilting use particular trajectories of light rays.

9203-10, Session 2

Mode-mode interference sensor with increasing number of modes along the multimode optical fiber

Oleg Kotov, Ivan Chapalo, Andrey Medvedev, St. Petersburg State Polytechnical Univ. (Russian Federation)

One of the distributed fiber optic sensors types is a sensor based on interference between modes in multimode fiber. Its operating principle is to analyze the speckle pattern at the output of the fiber. The advantages of this type of sensors are simplicity and relatively low cost. But the absence of signal dependence from the coordinate of the external fiber perturbations essentially limits its field of applications.

In this work the problem of external perturbations localization was investigated for a scheme with increasing number of modes along the fiber. Theoretical model which allows to obtain output signal dependencies from number of mode groups propagating at the point of perturbation was developed. Also experimental investigations which qualitatively confirm theoretical results were carried out. Experimental setup included three identical multimode fibers connected in series. In each fiber different number of modes was launched. The number of excited modes increased with number of fiber. In the first fiber only the lowest order modes were propagating. In the last fiber the modal power distribution was nearly uniform. So detected output speckle pattern was formed by this almost full mode structure. The results of the experiments demonstrated the differences in the output signal depending on which of the fibers subjected to perturbations. In case of large amplitudes of external perturbations the differences were observed in frequency spectrums of signals and in case of small amplitudes of perturbations the differences were observed in amplitudes of signals.

The results of the work can be fundamental for a new solution of localization task for distributed optical fiber sensors based on mode-mode interference in multimode optical fiber.

9203-11, Session 3

A comparative study between deflectometry and shearography for detection of subsurface defects *(Invited Paper)*

Philipp Huke, Jan Burke, Ralf B. Bergmann, Bremer Institut für angewandte Strahltechnik GmbH (Germany)

Nondestructive testing of objects is the basis for quality control in a production line. There exists a wide range of optical and tactile methods for the detection of surface defects. For hidden defects (below the surface) optical methods need a supporting load which generates a signal corresponding to the defect. Typically, the surface or the surface gradient of the specimen in a loaded and an unloaded state is measured and compared afterwards. The evaluation of shape differences is easier than measuring absolute shapes because systematic errors (e.g. calibration) cancel themselves out and the resolution mostly depends on the measurement system's sensitivity.

We compare shearography and deflectometry, identify relevant parameters and show restrictions of both methods with regard to the used systems. We present measurements on different specimens with a range of defects and show how these results can be compared. We discuss the feasibility of both methods and the used systems for the application in a production line with respect to parameters concerning the quality control of produced goods.

9203-12, Session 3

Stability of absolute depth reconstruction from deflectometric measurement data

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For a long time, the problem of reconstructing specular surface shapes from deflectometric registration data was considered inherently ambiguous, and thus requiring additional information, determining the absolute surface position. In 2013, Liu, Hartley and Salzmann suggested a solution to the reconstruction problem, which employed the first-order derivatives of the registration data in order to recover the absolute depth of the surface along each camera ray. In this work, we demonstrate an alternative derivation of equivalent results, leading to more computationally efficient and tractable expressions. Re-formulated in terms of normal vector field, our results provide a natural regularization that together or without external regularization data could be easily used within the existing reconstruction algorithms. We further elaborate on the stability and the uniqueness of the solution. In particular, we find that most common shapes (e.g. those that are locally well-approximated by spheres or planes) exhibit only isolated lines where the reconstruction is impossible and could thus be reliably reconstructed under mild additional assumptions.

9203-14, Session 3

Measuring deformations with deflectometry

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Phase-measuring deflectometry is a powerful method to measure reflective surfaces. It is relatively easy to extract slope and curvature information from the measured phase maps; however, retrieving shape information depends very sensitively on the calibration of the camera and the geometry of the measurement system. Whereas we have previously demonstrated shape uncertainties below 1 µm, the range below 100 nm is currently inaccessible to deflectometric shape measurement.

On the other hand, the astounding sensitivity of deflectometry can be put to good use for deformation measurements. The evaluation of corresponding shape differences rather than absolute shapes is much less susceptible to system calibration errors and its resolution is given mostly by the measurement system's sensitivity.

We give an overview of recent progress in difference deflectometry. Firstly we show results from solar mirror substrates under load to detect flaws with high sensitivity. The results will also be compared with interferometric shearography measurements.

Secondly we present a preliminary simulation study of achievable deformation-measurement uncertainties to assess the feasibility of deflectometric characterisation of actuator performance and gravity sag for the mirror segments of the European Extremely Large Telescope (E-ELT). Results for the relevant Zernike terms show reliable detection of Zernike coefficients at the 25 nm level. Random artefacts related to noise in the phase measurements are seen to translate into bogus Zernike terms, and we discuss possible mitigation techniques to enhance the sensitivity and accuracy further.

9203-15, Session 3

Spurious mid-spatial frequency structure on optical surfaces reconstructed from surface slope measurements

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Mid-spatial frequency structure on an optical surface induces small-angle scatter in the transmitted wave front. It is a concern in certain applications such as high power solid state laser systems, where initial perturbations evolve into filaments under the mechanism of small-scale self-focusing and finally damage the optical element. In state-of-the-art lithography applications, mid-spatial frequency structure leads to lens flare and image degradation.

Freeform optics is an emerging area that offers intriguing advantages to the final optical system. However, freeform surfaces are particularly susceptible to mid-spatial frequency errors due to the sub-aperture nature of the fabrication processes. Traditional optical testing techniques like interferometry are not applicable for most freeform surfaces. Several surface metrology methods that work for freeform surfaces use an indirect principle, such as reconstructing the surface shape from measured surface slope data. The integration process for the reconstruction adds a spatial correlation to the dataset; thus the spatial length scale of the noise in the measurement is larger in the reconstructed height map, leading to spurious spatial frequency structure.

This paper evaluates this artificial mid-spatial frequency structure on optical surfaces that are reconstructed by zonal integration methods, a family of path-integration approaches which cause artifacts by the global propagation of errors. Several mathematical tools are used for mid-spatial frequency structure specification/characterization, including the power spectral density, the auto correlation function and the structure function. We use these tools to analyze the relationship between the generated artifacts and the initial noise in the slope data.

9203-41, Session 3

A trial for a reliable shape measurement using interferometry and deflectometry

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Phase measuring deflectometry is an emerging technique to measure specular complex surface, such as aspherical surface and free-form surface. It is very attractive for its wide dynamic range of vertical scale and application range. Because it is a gradient based surface profilometry, we have to integrate the measured data to get surface shape. It can be cause of low accuracy. On the other hand, interferometry is accurate and well-known method for precision shape measurement. In interferometry, the original measured data is phase of interference signal, which directly shows the surface shape of the target. However interferometry is too precise to measure aspherical surface, free-form surface and usual surface in common industry. To assure the accuracy in ultra precision measurement, reliability is the most important thing. Reliability can be kept by cross-checking. Then I will propose measuring method using both interferometer and deflectometry for reliable shape measurement. In this concept, global shape is measured using deflectometry and local shape around flat area is measured using interferometry. The result of deflectometry is global and precise. But it include ambiguity due to slope integration. In interferometry, only a small area can be measured, which is almost parallel to the reference surface. But it is accurate and reliable. To combine both results, it should be global, precise and reliable measurement. I will present the concept of combination of interferometry and deflectometry and some preliminary experimental results.

9203-16, Session 4

Effect of alignment and tolerances on reverse raytrace calibration

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There are several sources of error in interferometry to consider when testing surfaces in a non-null configuration. A model of the interferometer is typically used to calibrate these errors but the model differs from the actual interferometer due to the alignment and tolerance of individual components. Reverse raytrace calibration using a model that differs from the real system corrects some errors but introduces others. Reverse optimization using measurements from known test configurations or configuration changes can produce a model that better reflects the real system. This paper addresses the tolerances required to obtain calibration precision from reverse ray tracing without reverse optimization. The sources of error can be separated in a way that allows the amount of correction to be compared to the generated errors from misalignment. These errors can be expressed in a generic way and applied to any arbitrary interferometer architecture or test surface shape. The simulation results of a standard interferometer with standard tolerances shows that errors corrected by reverse ray tracing can be on the same order as the errors generated by reverse ray tracing an incorrect model. The efficacy of the calibration method resides in correction of other errors such as distortion and ray intercept coordinate error. These corrections are much larger than misalignment errors for surfaces with large departures. This method can be used to determine the level of interferometer component alignment required to accurately measure large departure surfaces with reverse ray tracing.

9203-17, Session 4

Characterization of field dependent aberrations in Fizeau interferometer using double Zernike polynomials

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Fizeau interferometer is widely used to test surface deformations of optical elements. However, some measurements circumstances negate the common path condition of the Fizeau configuration, as the sub-aperture scanning interferometry of asphere or rotational scanning measurement. Systematic aberrations of non-null testing are introduced into the measurement wavefront. By using a two dimension scanning device to drive the tested lens to different field of the Fizeau interferometer, we can acquire the interference phase at each field with different tested wavefront slopes. Thus, we can get a two dimension matrix at different field of the interferometer, for each element of this matrix is a circular pupil phase with different wavefront slopes, so it's a four dimension matrix. In this proposed research paper, we used the double Zernike polynomial function to analyze this four dimension matrix. By using least squat fit this matrix to get the double Zernike polynomial coefficients which of the full-field wavefront represent the global optical aberration of the interferometer system. According to the coefficients, the system aberration can be compensating pixel by pixel at the corresponding wavefront slopes.

9203-18, Session 4

A large field-of-view scene measurement based on control points with a single camera

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The paper proposed a large field of view (FOV) measurement with calibrating the camera and measuring simultaneously. In the measurement, the whole FOV was divided into several smaller ones with overlapping areas between each other. The overlapping areas should contain at least 4 noncollinear feature points in each for computing external parameters and at least 4 noncollinear control points in one of them to start the calculation. To obtain the measurement of the whole large FOV, 2 images (or more) of each small fields of view needed to be taken from different angles. In the process of calculation, theoretical values of the camera were used as the initial values of the internal parameters and the initial values of external values were obtained from a new solution for P4P problem. So, the internal parameters of the camera, the external parameters for each image, and the 3D coordinates of the feature points in the large field of view could be acquired by adjustment method. In our experiment, the large field of view range was 500mm?500mm, the smaller ones corresponding to each image was 200mm?200mm, and the ultimate measurement accuracy was 12?m.

9203-19, Session 5

Hilbert-Huang processing and analysis of complex fringe patterns *(Invited Paper)*

Maciej Trusiak, Krzysztof Patorski, Maciej Wielgus, Warsaw Univ. of Technology (Poland)

Single-frame fringe pattern processing and analysis is a very important task encountered in optical interferometry, structural illumination and moiré techniques. To boost the accuracy of optical measurements several operations are preformed, mainly fringe pattern noise suppression, background removal, normalization, and amplitude/phase demodulation.

In this contribution we present several algorithmic solutions based on the notion of Hilbert-Huang transform (HHT). It comprises empirical mode decomposition (EMD) algorithm used to prepare a signal for subsequent Hilbert spectral analysis. EMD is an adaptive and data-driven algorithm proposed as an alternative to linear integral transform methods. Unlike the Fourier-based approaches EMD is not bounded by fixed basis functions and uncertainty in time-frequency localization (representation). As its key feature EMD adaptively dissects a rather small, meaningful number of so-called intrinsic mode functions (IMF) from the analyzed signal. IMFs are orthogonal oscillatory AM/FM components representing signal features varying on different scales. Appropriately managing a set of IMFs one can obtain a very powerful signal processing tool.

We describe in details especially tailored manners proposed to extend the EMD algorithm to 2D and perform Hilbert-transform-aided efficient fringe pattern denoising, detrending and amplitude/phase demodulation. Unprecedented adaptivity of the proposed advanced solutions enables successful analysis of a wide variety of challenging fringe patterns (exhibiting severe noise pollution, uneven background, amplitude modulation variation and considerable fringe frequency changes) without resorting to additional algorithm tuning. Experimental studies using moiré techniques, speckle interferometry, grating interferometry, time-averaged vibration amplitude profilometry and fringe projection techniques corroborate the versatility and robustness of the proposed HHT-based algorithms.

9203-20, Session 5

Improvement of defect detection in shearography by using principal component analysis

Jean-François Vandenrijt, Nicolas Lievre, Marc P. Georges, Univ. de Liège (Belgium)

A new post-processing technique based on principal components analysis (PCA) is proposed for shearography in view of easing defect detection. In nondestructive testing the PCA is already largely applied in thermography where temporal series of thermograms show tiny temperature differences at defect location when a thermal wave travels through the inspected object. In the case of interferometric methods like shearography, one needs to first apply a temporal unwrapping of the time series of interferograms and then apply PCA. The result of PCA is to decompose the time series of images into a set of images called Empirical Orthogonal Functions (EOF), each showing features with a given variability in the time series. PCA is a statistical analysis technique contrarily to Fourier analysis, the latter being deterministic in the sense that a set of orthogonal functions are a priori imposed.

We have applied PCA on composite samples containing various defects at different depths and which undergo transient thermal wave. Analysing the temporal series shows the shallow defects appearing first whereas the deeper ones appear later. With PCA all the defects appear in one or two of the EOF, easing the identification of defects.

9203-21, Session 5

Links between fringe pattern analysis and digital image correlation: windowed, optimal, and tracking (WOT)

Kemao Qian, Nanyang Technological Univ. (Singapore)

Fringe patterns and digital speckles are two basic carriers in optical measurement. The former adapts a regular sinusoidal form while the latter utilizes the randomness of speckles. As a consequence, fringe pattern analysis and digital image processing are quite isolated. However, if we look carefully, both of them attempt to extract desired information from the measured data.

In this paper we explore high similarities between fringe pattern analysis and digital image correlation. In principle, maximum likelihood estimation is appreciated in both areas in order to achieve the highest precision. In implementation, windowed process together with quality guidance has been widely used. We will look into details of these interesting aspects. The difference between two approaches will also be examined, which leads to different implementations. This paper is an extension of our paper five years ago.

9203-22, Session 5

Wavelet transform: capabilities expanded

Krzysztof Pokorski, Krzysztof Patorski, Warsaw Univ. of Technology (Poland)

Two dimensional Continuous Wavelet Transform (2D CWT) has become an important tool in the field of fringe pattern processing. It has modest requirements concerning fringe shape and spatial frequency, is known for its abilities to filter out high frequency noise and low frequency background, and can cope with low contrast fringes and local acquisition quality errors. Traditionally, the technique was used to analyze phase and modulation distributions of fringe patterns not easily processed using the Fourier transform i.e., fringe patterns with complex phase and amplitude distribution. We have developed new algorithms that significantly broaden the scope of 2D CWT applications.

Firstly, we proposed an algorithm to demodulate the phase of multiple fringe sets superimposed in a single image [Appl. Opt. 51, 8433-8439 (2012)]. We used novel ridge extraction algorithm based on constricting possible angle and scale differences in adjacent pixels, aided by the novel quality map, which determines the pixel processing sequence. Spectral separation of fringe families is not required.

Second part of the proposed advancement is the method for demodulating fringe patterns containing contrast reversals [Opt. Express 21, 22596-22609 (2013)]. First, the absolute value of the fringe intensity distribution with its background removed is calculated. Then, 2D CWT with enhanced ridge extraction algorithm is applied to extract the fringe

phase map. Proposed approach allows to dispose of phase jumps along the contrast reversal bands – the issue not addressed by any of the existing fringe processing methods.

Experimental data and simulations are presented to verify the method performance and advantages over the Fourier transform method.

9203-23, Session 6

Estimation of the temperature of a flame with asymmetric profile

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The large number of projections needed for tomographic reconstruction makes prohibitive the use of algebraic methods for fast phase object reconstruction. However, for smooth and continuous phase objects, the reconstruction can be performed with few projections by using an algorithm that approximates the phase as a linear combination of gaussian basis functions. This work presents an accurate algebraic reconstruction of a flame temperature from two orthogonal projections obtained from two independent interferometers using a He-Ne laser (623.8nm).

9203-24, Session 6

Performance evaluation of a phase retrieval algorithm from sequences of interferograms with unknown phase shifts using generalized N-dimensional Lissajous figures

Armando Albertazzi Gonçalves Jr., Analucia V. Fantin, Mauro E. Benedet, Daniel P. Willemann, Allison F. Maia, Univ. Federal de Santa Catarina (Brazil)

There is a large variety of strategies and algorithms for phase retrieval in interferometry. Phase shifting is certainly the most used and accurate approach. It combines data from a sequence of interferometric images mainly with very well defined phase shifts between them. The number of phase shifted images involved, as well as the amount of phase shifting between images, may vary significantly. Sometimes interferometric measurements have to be done in unstable environments, what produce unwanted movements in the interference signal. Although the undesired motion could be frozen applying, for instance, short laser pulses, it becomes difficult, or even impossible, to apply predefined phase shifts in an accurate way. The resulting phase shifts are rather unknown. This paper presents an alternative approach to retrieve phase information from a sequence of interferograms with unknown phase shifts using generalized N-dimensional Lissajous figures. Lissajous figures are very frequently used to compare two sinusoidal signals. The frequency ratio and the relative phase between the two signals can be determined from a 2D plot where each time dependent signal is assigned to the X and Y axis simultaneously. Lissajous figures can also be obtained by plotting light intensity of two separated pixels of a sequence of interferograms in the X and Y axis while the phases of the iterferograms are shifted continuously. The resulting Lissajous figure is an ellipsis. Depending on the choice of the points on the interferogram the figure can become a circle. In this case the phase shifts are easily determined by rotation angle of the plotted point along the circle line regarding the center of the circle. However, a bad choice of the two points can produce a much flattened ellipsis or even the ellipsis can degenerate to a straight line, making very difficult of impossible to determine the rotations and phase shifts. Since it is difficult to predict the behavior of the pair of selected points, this is not a very robust approach. To improve robustness, more data is added. If the signal of a third point on the interferogram is assigned to the Z axis, an ellipsis in 3D space is produced. By considering additional points a hiperellipsis is defined. If a total of N different pixels are taken from the intrferogram, a N-dimensional hiperellipsis is defined. The propabiblity to obtain a flattened hiperellipsis decreases as N increases. Data from a series of at least six interferometric images with unknown phase shift are used to determine the hiperellipsis parameters and, from those, the relative phase shifts. The paper presents also a generalized algorithm for computing phase values for each pixel of the image from a set of irregular phase shifted images. Few applications are given for shearogaphy images.

9203-25, Session 6

Design of new window function of phase extraction algorithm in wavelength tuning Fizeau interferometer

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Wavelength tuning interferometry allows the simultaneous measurements of the surface shape and deviation component of optical thickness of a transparent plate. The modulation frequency is proportional to the optical path difference between the two reflecting surfaces. The simultaneous measurement of the surface shape and the refractive index inhomogeneity of a plate was first demonstrated in a wavelength tuning Michelson interferometer.

In this presentation, we derive new 4N – 3 algorithm including new window function and discrete Fourier transform that can compensate for the effect of frequency detuning and suppress the multiple-beam interference noise. The new window function consists of the polynomial and by using this polynomial window function the second order nonlinearity error of the phase-shift can be compensated. The sampling functions for the new algorithm have much smaller amplitudes in the vicinity of the detection frequency than the synchronous algorithm, Surrel's 2N – 1 and Hanayama 2N – 1 algorithms. After recording 4N – 3 image frames with an equal wavelength interval, the new algorithm can detect the phase of an arbitrary order of harmonic frequency, whose flexibility is similar to that of the synchronous algorithm and Hanayama 2N – 1 algorithm. The new algorithm can measure the surface shape and optical thickness deviation of a transparent plate consisting of more than three surfaces and can be applied to highly-reflective Fizeau interferometer.

9203-27, Session 6

Application of a swarm-based approach for phase unwrapping

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An algorithm for phase unwrapping based on swarm intelligence is proposed. The novel approach is based on the emergent behavior of swarms. This behavior is the result of the interactions between independent agents following a simple set of rules and is regarded as fast, flexible and robust. The rules here were designed with two purposes. Firstly, the collective behavior must result in a reliable map of the unwrapped phase. The unwrapping reliability was evaluated by each agent during run-time, based on the quality of the neighboring pixels. In addition, the rule set must result in a behavior that focuses on wrapped regions. Stigmergy and communication rules were implemented in order to enable each agent to seek less worked areas of the image. The agents were modeled as Finite-State Machines. Based on the availability of unwrappable pixels, each agent assumed a different state in order to better adapt itself to the surroundings. The implemented rule set was able to fulfill the requirements on reliability and focused unwrapping. The unwrapped phase map was comparable to those from established

methods as the agents were able to reliably evaluate each pixel quality. Also, the unwrapping behavior, being observed in real time, was able to focus on workable areas as the agents communicated in order to find less traveled regions. The results were very positive for such a new approach to the phase unwrapping problem. Finally, the authors see great potential for future developments concerning the flexibility, robustness and processing times of the swarm-based algorithm.

9203-26, Session PMon

Phase unwrapping using a surface mesh with constraints

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Phase unwrapping is an intermediate step for interferogram analysis. The phase associated with an interferogram can be estimated using a curve mesh of functions. Each of these functions can be approximated by a linear combination of basis functions. Sometimes you need to add restrictions, for example, when estimated values never can be negative.

Chebyshev polynomials in addition to being a family of orthogonal polynomials can be defined recursively. In this work a method for phase unwrapping using Chebyshev polynomials with constraints is proposed. Results show good performance when applied to synthetic images without noise and also to synthetic images with noise.

9203-40, Session PMon

Fiber optic laser Doppler velocimeter with non-mechanical scanning of spatially encoded points for cross-sectional velocity distribution measurement

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Differential laser Doppler velocimeters (LDVs) have been widely used for industrial and research applications. For practical use, an LDV with a compact probe is desired, and two-dimensional velocity distribution on a cross-sectional plane of flow needs to be measured in many applications. Here, we propose a fiber-optic LDV combining non-mechanical scanning using wavelength change and simultaneous multipoint measurement using multiple optical frequency shifting. The LDV consists of a main body including a tunable laser and LiNbO_3 phase-shifter array, and a probe including diffraction gratings. The beam from the tunable laser is divided into two beam arrays, and one of these beam arrays is modulated with different frequencies by multichannel optical serrodyne modulation with the phase-shifter array. The beam arrays are input to the probe via fiber arrays and diffracted by the gratings. The beam arrays cross each other and generate spatially encoded measurement points aligned along the transverse direction. These measurement points are axially scanned by the change in diffraction angles with the wavelength change. The scattered beams are monitored with a single photodiode. This LDV requires only a reasonable number of phase shifters because of the combination of scanning and spatial encoding. The use of the LiNbO_3 phase-shifter array allows us to simplify the generation of the spatially encoded points compared with the use of acousto-optic modulators. The probe can be simple and reliable because no moving mechanism is needed in the probe. The experimental results will be presented and discussed at the conference.

9203-44, Session PMon

Experiment analysis of freeform testing based on absolute testing method

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Recently, optical components with freeform surface have been widely used in many optoelectronic systems because they can correct several image aberrations effectively and simplify optical system structures. Freeform surfaces described by ?-polynomials are under active development and integration in all aspects-optical design, optical fabrication, optical component testing, optical system alignment and optical system testing. With the development of nanofabrication and testing technology, freeform surfaces are increasingly used in the design of compact optical systems. Freeform lens can be used to compensate the wavefront errors in the optical system. Freeform optical surfaces with aperture of 1-300mm, surface roughness of sub-micro or nanometer level, and surface vertical range above 100-um level, can still hardly be tested in workshop economically, simply, and quickly. The freeform lens for wavefront compensating contains some medium spatial frequency terms. The absolute testing method is used to improve the testing accuracy. In this paper we will show the testing experiment of the freeform. In this paper the freeform surface is created by 66th Zernike polynomials. The freeform lens is based on the flat lens. The freeform flat which we use is polishing by the ion figuring machine of NTG. The environment such as temperature, vibration, humidity is controlled well. The Zygo's interferometer Verifire Ashpere with absolute testing method is used to test the freeform. Position Accuracy is a problem in optical testing and manufacture. we hope to get an RMS 1nm(the data of design freeform minus testing result) in the future.

9203-48, Session PMon

Digital holographic moiré pattern for optical numerical code generation

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Digital Fourier transform holography can be used to produce sinusoidal interferometric moire-like patterns. This moiré patterns are defined as optical bits for numerical code generation. A binary numerical base was defined with the phase of specific moiré patterns representing 0, 1, -1 and 2 digits like bits. The complete set of these optical bits are combined to form bytes, where a numerical sequence could be represented. The system includes the experimental setup and robust manipulation of algorithms for bytes definition and codification. It is an alternative as an optical numerical code generation for secure manipulation of data for many purposes.

9203-50, Session PMon

Measure of a zinc oxide (ZnO) film thickness using a point diffraction interferometer

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The zinc oxide (ZnO) is used as transparent conductive layers in blue light-emitting diodes, liquid-crystal screens, varistors, and thin-film solar cells and gas sensor among others. An important element in structural characterizations is the measurement of the thickness of thin film deposition on substrate. In this work, an optical method for measurement of thickness of a ZnO film, in this case a point-diffraction interferometer (PDI) is used. The PDI uses few optical elements in the arrangement and

its low cost shows in an easy implementation. Also, the ZnO sample does not require any chemical treatment to be measured; consequently, it does not need an extra step in the measurement process. The purpose of the arrangement is to implement it as a measuring tool for laboratory of sensor films of the Autonomous University of the State of Hidalgo. For early results, it is proposed to measure the ZnO film thickness larger than one micron, and the results are compared with the traditional method using a talkstep.

9203-51, Session PMon

An interferometric humidity sensor based on a thin gelatin film

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Optical interferometry is a powerful and versatile tool that has been applied in high performance sensors. Various interferometer configurations such as the Mach-Zehnder, Michelson, Sagnac and Fabry-Perot can be used to perform the detection. Here we suggest and show an optical method based on a small Mach-Zehnder interferometer to measure relative humidity (RH). The sensitive device is a gelatin thin film (20 microns). Gelatin is a hydrophilic material. If a gelatin thin film is immersed in an environment with a given RH it will sorb (desorb) water vapor. This absorption (desorption) is done gradually. This absorption (desorption) of water vapor will affect the gelatin refractive index and its thickness. In order to study the behavior of the gelatin with humidity a climatic chamber was built. In the chamber a Mach-Zhender interferometer was placed. Then a gelatin film was introduced in one arm of the interferometer. Due to the change in humidity the thin film began to swell and therefore interference fringes moved horizontally. To detect this movement a detector with a pinhole was placed after the interference pattern. Calibration plots showing the behavior of intensity as a function of the relative humidity were obtained.

9203-52, Session PMon

IDIA: doubling the recorded imaging area or the frame rate in off-axis interferometric microscopy

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We present the metrology technique of interferometry with doubled-imaging area (IDIA), a new holographic principle and an optical configuration that are capable of doubling the off-axis interferometric FOV. This technique enables imaging up to twice the amount of off-axis interferometric information in a single camera exposure, or increase the acquisition rate while capturing half of the original FOV, and still reconstructing the full original FOV, as the frame rate and imaging area are interchangeable. Our first implementation is based on a compact, portable, and inexpensive interferometer, connected to the output of a regular transmission microscope, turning it into a powerful interferometric microscope with a wider FOV. We demonstrated the proposed technique for scan-free quantitative optical thickness imaging of microscopic samples and biological samples, including live neurons.We also demonstrated rapid high-magnification imaging of a human sperm cell in motion, as well as nondestructive quality-testing profilometry during a rapid lithography process of transparent structures.

9203-53, Session PMon

Periodic error characterization in commercial heterodyne interferometer using an external cavity diode laser based Fabry-Perot interferometer

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Heterodyne laser interferometry is widely used in numerous high precision displacement measurement applications. However, periodic error exists and limits the measurement accuracy. The measurement and characterization of the periodic error remains an important aspect in heterodyne interferometry. We built a new single resonance tracking Fabry-Perot interferometer for direct periodic error characterization. The system is composed of two parts: Fabry-Perot cavity resonance tracking and single optical frequency synthesizer. An external cavity diode laser (ECDL1) and a high finesse confocal Fabry-Perot cavity are used as the laser source and the displacement sensor, respectively. ECDL1 is locked to the cavity resonance using Pound-Drever-Hall frequency locking technique. Thus, the displacement of the cavity mirror is converted to the ECDL1 frequency change, which is measured by beating with the single laser frequency synthesizer. The laser frequency synthesizer includes a second laser ECDL2 and an optical frequency comb locked to Rb clock. With the help of the developed system, ECDL2 frequency can be locked to any selected comb mode, generating a stable and traceable optical frequency. The Allan deviation of the frequency synthesizer is 1.8 ? 10-12 at 1s averaging time. Experiments show that our built Fabry-Perot interferometer has a resolution of 1.2pm at the averaging time of 10 ms. A commercial plane mirror heterodyne interferometer is set up, with the Fabry-Perot probe mirror as the measurement target. The measured displacements of the heterodyne interferometer are compared with the Fabry-Perot interferometer. After linear fit, the first harmonic periodic error is detected, with amplitude of 4.6nm.

9203-54, Session PMon

Shaping intensity behind amplitude masks for proximity correction lithography: design, measurement, and realization

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Nowadays equipment for projection lithography is rather expensive because of the sophisticated lens system needed for its operation. In that case cost efficient proximity lithography printing can be used, so nearly all producers of semiconductors use mask aligners for less critical layers. In proximity printing, the light intensity distribution behind the photo mask is affected by diffraction effects governed by the distance between mask and wafer. A resolution enhancement in proximity lithography is possible using Optical Proximity Correction (OPC) structures. Today's optimization is mainly based on trial and error. In our approach simulated proximity correction structures are designed with Layout Lab (GenISys GmbH) and the result is compared with measured light intensity distributions behind the mask using a High Resolution Interference Microscopy (HRIM).

HRIM is basically a Mach–Zehnder interferometer which is capable of analyzing 3D –light distributions. The interferometer applies phase shifting interferometry which allows precise extraction of information and records the real three-dimensional amplitude and phase fields by scanning the samples in the axial directions. The light source adapted to photolithography is a 405nm violet- blue laser, the same illumination as used in simulations.

Here we present an example of optical proximity correction done for the study of edge slope improvement. Simulation and measurements are compared to the design for different structures [Structures are periodic in y-direction] where a simple edge is used as reference. Different proximity gaps form 30um to 100um are considered and it will be shown how the OPC influences the steepness and position of the edge to be printed.

9203-29, Session 7

Interferometric microscope with true color imaging

Jake L. Beverage, Xavier Colonna De Lega, Martin F. Fay, Zygo Corporation (United States)

Optical profilers based on Coherence Scanning Interferometry (CSI) provide high-resolution non-contact metrology for a broad range of industrial applications. As the breadth of CSI applications expands toward defect detection and inspection there is interest in capturing accurate color information as an additional metrology channel. Besides rendering realistic-looking 3D images, color data facilitate the detection of defects, blemishes or discolorations that are otherwise invisible in topography data. Other uses include image segmentation, detection of dissimilar materials and edge enhancement.

This paper reviews the benefits and drawbacks of options for capturing color information. Emphasis is on their impact on the surface metrology capability of the instrument (lateral resolution and height-measurement precision) and the flexibility they offer in terms of image sensor choice. For instance, a single-sensor camera with Bayer filters achieves the goal of color imaging, but at the expense of reduced lateral sampling of the image plane and additional pre-processing in order to reconstruct a metrology signal equivalent to that provided by a monochrome sensor. Another approach is a multi-camera system (e.g. 3-CCD) with color filters over each camera, which recovers image sampling density but is costly and limits sensor choices.

In this context, we consider the benefits of an alternative solution for which there are no color filters at the camera and the spectral reflectivity information follows from unique data capture and processing procedures. This approach synthesizes full true-color overlay onto areal surface topography maps at the same lateral sampling as the camera, while retaining the vertical resolution of traditional monochrome systems. The paper will detail the necessary hardware and software, and provide several examples illustrating the benefit of true color and 3D topography image fusion.

9203-30, Session 7

Dual-wavelength diffraction phase microscopy for real-time dispersion measurement

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We report on the multi-wavelength diffraction phase microscopy that obtains the wavelength-differentiated phase images at a single shot of interference fringe acquisition. For this, the diffraction phase microscopy system was constructed with a transmission grating and a spatial filter that form a common-path interferometer. With a light source of multi-spectral components, a different diffraction order of the grating was utilized for each. This resulted in a combined but distinguishable interference pattern to be acquired by a single image sensor at once. In this research, our multi-wavelength phase imaging scheme was applied to high speed measurement of sample dispersion. Stable and reliable measurement could be performed in a single shot due to the robust structure of our multi-wavelength diffraction phase microscopy system. We found that our multi-wavelength diffraction phase microscope provides an accurate measurement of different phase objects such as Sillica bead and optical fiber with good measurement stability that comes from the common-path geometry. Multi-wavelength acquisition capability was achieved without major changes to the system geometry but by simply optimizing the system parameters with a multi-wavelength light source. The system simplicity in terms of structure, signal processing, and operation scheme makes multi-wavelength diffraction phase microscope highly attractive for various applications.

9203-31, Session 7

Reduction of the stagnation effect by combined iterative and deterministic single beam phase retrieval techniques

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Single beam phase retrieval techniques [1-3] allow the reconstruction of the object phase information for single beam devices such as optical microscopes. These techniques are well-suited for simple optical setups and recover the phase using the intensity recorded at a single or multiple planes. Available Iterative Phase Retrieval (IPR) techniques as the Single-Beam-Multiple-Intensity-Reconstruction (SBMIR) algorithm [2] are applicable to the non-paraxial case without imposing restrictions on the object to be investigated. However, this family of IPR techniques are subject to varying levels of performance or stagnate after few numbers of iterations. The stagnation is a result of the slow elimination of the remaining low frequency error components in form of a phase tilt, a bell-shaped error, or other low frequency artifact. This problem results in a poor phase reconstruction, especially for the case of slow-varying objects. A recent work [4] presents an Wigner diagram analysis on the convergence of iterative SBMIR solvers due to the influence of the image formation system and wave propagation errors. Reference [4] proposed the use of a sufficient diversification within the captured intensities and showed that the use of relaxation and multi-resolution strategies [5] help to reduce the stagnation of the SBMIR algorithm.

In this work, the stagnation problem in iterative SBMIR algorithms is overcome by incorporating deterministic phase retrieval techniques within the IPR to compensate for paraxial artifacts. The principle is based on the idea that once the iterative solver stagnates a deterministic phase retrieval technique [6] is employed to correct the low-frequency errors in the retrieved phase. Those hybrid deterministic-iterative single beam phase retrieval techniques allow the successful compensation of the low frequency artifacts. These techniques can be understood as a paraxial ray correction for IPRs. It is shown that these techniques can be successfully employed for cases where a iterative solver is trapped in a local minimum, or allow increasing the convergence of SBMIR solvers that employ relaxation and multi-resolution strategies [5].

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9203-32, Session 7

Comparison of full-field interferometric measurement techniques applied to small vibration amplitudes determination

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Laser Doppler Vibrometry (LDV) is considered to be the most accurate optical measurement method applied for harmonic motion investigations. As it is a point-wise method, however, it requires and additional scanning to obtain an amplitude distribution over the object under test. Depending on the strategy of scanning the measurement time may be elongated considerably. For fast measurement time the full field methods are preferable. The most widely used are the time-averaging and stroboscopic interferometry. Unfortunately both methods require an amplitude magnitude of at least 0.19*lambda to be able to detect resonant frequency of the object. Moreover the precision of measurement is limited. That puts strong constrains on the type of element to be tested.

In this paper the comparison of two methods of microobject vibration measurements that overcome aforementioned problems are presented. First on is the classical two-beam heterodyning interferometry with time-averaging. The second one is the method that employ Smart-Pixel camera with special demodulation mode. Both methods maintain high speed measurement time and extend the range of amplitudes to be measured (below 0.19*lambda), moreover can be easily applied to MEMS/MOEMS dynamic parameters measurements, especially for resonance vibration's amplitude and phase evaluation. Large part of the work is devoted to extensive numerical simulations of two aforementioned methods. During numerical simulations the different measurement conditions were simulated. The results of amplitude and phase recovery were compared to nominal values thus error distribution and accuracy analysis was performed. Experimental verification of the numerical simulations findings was performed with two different measurement setups.

9203-33, Session 7

Three-dimensional photothermal microscopy of KDP crystals

Jian Chen, Jingtao Dong, Qi Zhang, Zhouling Wu, ZC Optoelectronic Technologies, Ltd. (China)

The laser damage threshold of KDP crystals is one major limitation in many high-power laser systems. Investigation of laser damage behavior of KDP crystals show that the major reason for laser damage is the growth defects in the bulk of the materials.

Therefore, an effective diagnostic method for those defects is quite necessary for producing KDP crystals with high enough damage threshold to meet the requirement of high power laser applications.

In this paper, we reported the characterization of bulk defects in KDP crystals using a three dimensional photothermal microscope based on a laser-induced photothermal lensing technique. Several 3D mapping of the bulk defects were obtained. The results indicated that both surface defects and bulk defects can be determined and analyzed using the 3-D photothermal microscope.

The details of the development of the 3-D photothermal microscope were also presented. The system provides user-friendly operations of the defects characterization process and shows great potential of application for characterization of low absorption optical materials.

9203-34, Session 8

Overview of the optic component manufacturing and measurements for the Advanced Virgo optics *(Invited Paper)*

Andrew D. Nelson, Aleksandr Estrin, Zygo Corporation (United States)

Advanced Virgo is an upgrade to the Virgo detector located near Pisa, Italy designed with an ultimate goal of the detection of gravitational waves originating from cosmic sources. The upgrade will provide an order of magnitude increase in the sensitivity of the detector and allow the exploration of a volume 1,000 times larger than Virgo. The system design includes 21 half meter class optics and Zygo has been selected as the primary supplier. The component optics have nanometer level low-order figure requirements along with sub-angstrom roughness requirements (specified over a wide spatial frequency band). In this paper we will present the results and methodologies used in achieving such extreme requirements that are typically associated with the semiconductor lithography industry. We will also highlight how similar techniques are being applied on other materials for varied applications.

9203-35, Session 8

A novel linear Sagnac interferometer in position determination of perturbations

Shaohua Pi, Bingjie Wang, Jiang Zhao, Guangwei Hong, Dong Zhao, Bo Jia, Fudan Univ. (China)

A simple distributed optical sensing system for detecting and locating intrusion based on Sagnac interferometer is described. The sensor has a linear structure with the two arms in a two-core fiber optical cable. It owns a high sensitivity due to that the phase shifts in the two fibers are synchronous but opposite, namely when one fiber is compressed the other fiber is stretched, and vice versa. Experiments on simulating the intrusion in lab have been launched. A 50m resolution has been achieved when the intrusion distance is 100km. This structure is proved simple and accurate?

9203-36, Session 8

Effects of environmental instability on phase-sensitive optical frequency domain reflectometry

Martha I. Bodine, Univ. of Colorado at Boulder (United States); Eric D. Moore, Chiaro Technologies, LLC (United States); Robert R. McLeod, Univ. of Colorado at Boulder (United States)

Phase-sensitive optical frequency domain reflectometry (OFDR) is capable of absolute range measurements with sub-nanometer precision. However, measurement precision is susceptible to fluctuations in the surrounding environment. Here, we examine the effects of three sources of environmental instability: temperature changes during a single measurement and between measurements, vibrations, and electronic jitter. Additionally, we determine the contribution of each of these sources to the total uncertainty of range measurements.

9203-37, Session 9

High-speed 3D shape measurement with fiber interference *(Invited Paper)*

Beiwen Li, Iowa State Univ. (United States); Pan Ou, BeiHang Univ. (China); Song Zhang, Iowa State Univ. (United States)

High-speed, ultra-compact 3D shape measurement system is greatly needed in applications where the space constraints impose, and the motion involves. The state-of-art digital fringe projection (DFP) systems can generate high-quality measurement quality with high speed. However, the DFP systems are usually rather bulky and their miniaturization is nontrivial. The binary-defocusing based DFP techniques can achieve kHz 3D shape measurement rates, yet its speed bottleneck has arrived due the mechanical motion of the digital micro-mirror. This research endeavors to simultaneously address the speed bottleneck and the system miniaturization issues of the 3D shape measurement techniques. Instead of using a digital video projector, the proposed method uses two fiber wires that carries the same wavelength of laser light with polarization and phase information properly modulated to generate high-quality sinusoidal fringe patterns through interferences. Different breadths of fringe patterns can be generated either by changing the separation distance between two fiber wires. For high-quality 3D shape measurement, phase-shifting methods are usually used. To change the phase rapidly, a phase modulator is employed in this proposed system. Since the phase modulator can change the phase of the laser light at MHz even GHz rate, the proposed technique achieves unprecedentedly high speeds; and since only two fiber wires are used to generate sinusoidal patterns, the projection head can be much smaller than that of the digital video projectors. Principle of the proposed techniques will be introduced, and preliminary experimental results will be presented in this paper.

9203-38, Session 9

Microscopic type of real-time uniaxial 3D profilometry by polarization camera

Shuhei Shibata, Fumio Kobayashi, Daisuke Barada, Yukitoshi Otani, Utsunomiya Univ. (Japan)

Many non-contact measurement methods for optical three-dimensional surface have already been proposed. A stereo method is used for many variations such as a moire and a grating projection. However these methods can't apply a deep hole or steep height. Because fringe pattern in the bottom is hard to capture with shadow portion. To solve this problem, a method of uniaxial measurement of three-dimensional surface is introduced by polarization camera whose each pixel the polarizers attached on CCD. Their directions of polarizer array are composed to 0°, 45°, 90° and 135°. A polarization grating controlled in spatially using a quarter wave plate and a spatial light modulator is projected onto a sample. Intensity reflected from sample is detected by polarization camera. A contrast of projected sinusoidal pattern onto sample is approximated the Gauss distribution along depth direction. This contrast fitting to the Gauss function is measured in advance. This method can be analyzed the contrast distribution in real-time by 4 steps phase shifting technique using 4 pixels of different polarizer array. The three-dimensional coordinate calculates relationship the Gauss distribution and measuring contrast. We attempt real-time uniaxial three-dimensional profilometry in a microscope using polarization grating controlled by spatial light modulator.

9203-46, Session 9

Analysis of optimization method for interferometric evaluation of small shape deviations

Jiri Novak, Pavel Novak, Antonin Miks, Czech Technical Univ. in Prague (Czech Republic)

One of basic tasks in optical production is the testing the quality of optical surfaces and the determination of deviations of fabricated optical surfaces from their nominal shape, which are caused by the imperfect technological process of fabrication of optical elements. Optical surfaces should be fabricated within specified tolerances in order to satisfy production requirements. Several techniques were proposed in recent years. Interferometry represents the most frequently used group of very accurate testing methods of flat, spherical and rotationally aspheric optical surfaces. This work is focused on the description and analysis of a method for the evaluation of small deviations of optical surface shape in interferometric testing. The proposed method does not require to perform a detail analysis of the interference field as it is necessary with the classical evaluation methods of interference patterns and it uses the optimization techniques for the determination of the deviation of the tested surface from its nominal shape. This method compares interferograms, which correspond to the nominal shape of optical surfaces, and measured interferograms of the test surface using the suitable merit function based on variance of two interference patterns. It can be used for the comparison of two surface shapes. By optimization one can calculate unknown parameters which describe the difference between the test and nominal optical surface. The method is applicable for the testing of smaller deviations of the shape of optical surfaces. The method is analyzed on several examples of various shapes of optical surfaces with different optimization techniques and the influence of noise and nonuniform modulation of interferograms is investigated.

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9204-17, Session PMon

Error reduction method using two fringe projectors on 3D shape measurement

Motoharu Fujigaki, Atsushi Shima, Yorinobu Murata, Wakayama Univ. (Japan)

Non-contact shape measurement method is important for various fields. The phase-shifting grating projection method is often used for non-contact shape measurement. The phase analysis method is highly accurate. However, the accuracy of this method is not constant across a variety of objects. In a fringe projection method, much error occurs near boundary areas changing of reflectance.

In this study, authors found out the reason of the error and proposed a shape composition method with a weighted averaging method. The measurement error can be reduced using two projectors with composition of the two results with a weighted averaging method. The weight tables are generated using reference planes pixel by pixel when the phase-3D coordinates tables are generated by a whole-space tabulation method. In the presentation, the principle of the Error reduction method using two fringe projectors on 3D shape measurement and an experimental result are shown.

9204-20, Session PMon

Study of the stability and uncertainty of an external cavity diode laser through a Michelson wavemeter

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A Michelson wavemeter was developed to test the accuracy and give traceability to the wavelength of external cavity diode lasers. These lasers were stabilized using a Littrow configuration and an iodine gas cell as frequency reference, and they were used as light sources in the assembly of a new interferometric system for the gauge block calibration. Previously, the uncertainty evaluation of the Michelson wavemeter with a Vernier counter had to be made.

9204-21, Session PMon

MG63 cells behavior on rough polypyrrole scaffolds investigated by digital holographic microscopy

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We use polypyrrole thin films (fabricated by Matrix Assisted Pulsed Laser Evaporation), acting as substrates for osteoblast-like MG63 cells having applications in Tissue Engineering. These substrates are generally rough and therefore optical characterization of the attached cells is problematic. In this study, we employed digital holographic microscopy in order to obtain 3D images and rapid axial quantitative information for these samples. As a result, the cells contour was precisely identified and used for quantitative measurements concerning the transversal dimensions, filopodia lengths, eccentricity, by employing analytical or implicit digital filters with predefined thresholds. These data were correlated with the effects on osteoblasts viability and differentiation. The thickness and the refractive index of the substrate were determined using the decoupling procedure.

9204-22, Session PMon

Non-destructive testing of pressurized vessels by laser shearography and computational modeling

Morteza Khaleghi, Timothy R. Kurisko, Ivo Dobrev, Xiaoran Chen, Cosme Furlong, Worcester Polytechnic Institute (United States)

Pressurized vessels and pipelines are used in a variety of applications for storing and carrying many different liquids and chemicals. Structural health monitoring techniques are required to prevent, or at least minimize, catastrophic failures on these components. In this paper, we report the application of a method that combines laser shearographic techniques and computational modeling to perform non-invasive investigations of the structural response of a specific pressurized vessel under different loading conditions. Our shearography system is capable of concomitant measurements of the gradients of displacement along two orthogonal shearing directions. With recently incorporated capabilities that include both, real-time temporal phase unwrapping and high-resolution Fast Fourier Transform (FFT) methods for calibration of the applied shearing to set the sensitivity levels, the system enables a number of measuring modalities for applications outside the laboratory. Finite Element Methods (FEM) and fringe prediction are used to simulate different loading conditions in order to guide shearographic measuring procedures.

9204-23, Session PMon

Advanced laser shearographic system for in-situ non-invasive analysis of oil-on-canvas paintings

Morteza Khaleghi, Ivo Dobrev, Worcester Polytechnic Institute (United States); Philip Klausmeyer, Worcester Art Museum (United States); Xiaoran Chen, Ellery Harrington, Cosme Furlong, Worcester Polytechnic Institute (United States)

A proper evaluation of current condition standards commonly used for exhibiting canvas paintings requires a quantitative technique capable of measuring physical changes induced by variations in temperature and relative humidity, as well as the effects of ambient vibration and the thermo-mechanical effects of lighting. This research presents advances in developing a customized laser shearography system for temporal characterization of out-of-plane gradients of displacements of canvas paintings when subjected to changes in exhibition conditions. The system performs concomitant measurements of gradients of displacement along two orthogonal shearing directions and is synchronized with a thermal IR camera to provide thermal maps of the area analyzed. Due to the nature of the measurements, we have developed real-time temporal phase unwrapping algorithms and high-resolution Fast Fourier Transform (FFT) methods to calibrate applied shearing levels. Examples presented illustrate the system's capabilities to measure and map associated strain vectors as a function of changes in condition parameters. Included are representative results for a 19th-century oil on canvas monitored over the course of a 30-hour period under typical museum conditions.

9204-24, Session PMon

Blade counting tool with a 3D borescope for turbine applications

Kevin G. Harding, GE Global Research (United States); Jiajun Gu, Li Tao, GE Global Research (China); Guiju Song, GE Global Research (United States); Jie Han, GE Global Research (China)

Video borescope is widely used for turbine and aviation engine inspection to guarantee the health of blades and prevent blade failure during running. Blade counting tool is video interpretation software that runs simultaneously in the background during inspection. It identifies moving turbine blades in a video stream, tracks and counts the blades as they move across the screen. It contains two major steps, blade detection and blade tracking. Blade detection identifies leading edges for each blade in one frame. Before leading edge detection, frame is de-interlaced at first and enhanced by image preprocessing. Sobel operator is employed for image segmentation. An adaptive threshold algorithm is adopted to remove all background information. All potential leading edges contained in the binary image are extracted by Hough transformation. In practice, blade's leading edge is nearly perpendicular to turning direction. Based on this finding, noise edges are filtered. Blade tracking compares the blade detection result with that of previous frame. It categories the blades into three types, blades found in both two frames, blades found only in current frame and blades found only in previous frames. The blades contained in both frames are correlated to each other, taking their position, tracking history in to account. The blade that is new, which is only found in current frame, will be determined whether is noise, a new blade or a counted blade which turns back and shows again. The blade that is gone will be decided if it is temporary disappearance by detection failure or turning out of the screen. The blade position is updated to display a number indicator for each blade from the tracking result.

9204-26, Session PMon

A novel method for holographic femtosecond laser parallel processing using digital blazed grating and the divergent spherical wave

Chaowei Wang, Yahui Su, Jinli Wang, Anhui Univ. (China); Chenchu Zhang, Univ. of Science and Technology of China (China); Ziyu Zhang, Anhui Univ. (China); Jiawen Li, Univ. of Science and Technology of China (China)

A novel method for holographic femtosecond laser parallel processing is proposed, which can suppress the interference of zero-order light effectively and improve the energy utilization rate. In order to blaze the target pattern to the peak position of zero-order interference, a phase-only hologram containing digital blazed grating are designed and generated. The energy of the target pattern can be increased to 5.297 times in theory. In addition, by subsequently increasing the phase of the divergent spherical wave, the focal plane of the target pattern and the plane of multi-order diffraction beam resulted from pixelated structure of the spatial light modulator (SLM) can be separated. Both the high pass filter and aperture are used to eliminate the influences of zero-order light and multi-order interferential patterns simultaneously. A system based on the phase-only SLM (with resolution of 1920?1080) is set up to validate the proposed method. The experimental results indicate that the proposed method can achieve high quality holographic femtosecond laser parallel processing with a significantly improved energy utilization rate.

9204-1, Session 1

Microscopic contouring with low coherence interferometry endoscopy *(Invited Paper)*

Ben Buckner, Spectabit Optics, LLC (United States); Bauke Heeg, Lumium Optical Precision Instruments (Netherlands); Tom Jenkins, James D. Trolinger, MetroLaser, Inc. (United States)

Two optical methods are under investigation for the detection of damage on coated and uncoated airfoils in advanced gas turbines, by means of borescope inspection of on-wing parts. The techniques are low coherence interferometry imaging of bulk TBC optical properties and luminescence piezo-spectroscopy for imaging of residual stress in the thermally grown oxide layer at the ceramic-alloy interface. The work reported in this paper includes design, component testing, construction, and testing of the prototype instrumentation. The instrumentation provides a significant advance over currently employed visual inspection of gas turbine airfoils. For instance, with thermal barrier coatings (TBCs), these techniques allow the detection and quantification of incipient spalls, delamination, and changes in TBC porosity which typically go unnoticed with visual inspection methods. The methods are well suited for use with borescopes and thus provide a large potential to be developed into commercial optical diagnostics instruments for use during maintenance and inspection of on-wing airfoils in advanced gas turbines.

9204-2, Session 1

Endoscopic metrology for cardiovascular flows studies

Laura A. Arévalo-Díaz, Eva Roche, Virginia R. Palero, Nieves Andrés, Julia Lobera, Miguel A. Martínez, M. Pilar Arroyo, Univ. de Zaragoza (Spain)

The complete measurement of the blood velocity and the vein wall deformation is important in order to obtain the wall shear stress distribution in blood vessels. This information would facilitate the diagnosis and treatment of some cardiovascular diseases.

Endoscopic digital holography (EDH) has been developed to measure both the flow velocity and the wall deformation in vessel models with pulsatile flows. The models present different flexibility and opacity grades. Both the vessel model and the endoscope end are immersed in a refractive index matching liquid in order to avoid distortions. Thus, they can be used for observing inside opaque vessels in an oblique way. The recorded image will be affected only by perspective distortion that can be corrected numerically.

Endoscopes, which have the remarkable advantage of allowing the illumination and imaging of the object under inspection, have been also combined with high speed Particle Image Velocimetry (PIV) to measure the velocity field of a flow inside a transparent vessel model. Stereoscopic measurements can be done by using two endoscopes. The set-up shows great versatility, allowing the endoscopes to be moved as close as required, observing different regions. The vessel central plane is illuminated with a laser sheet, so instantaneous 2D-3C velocity fields of the pulsatile flow are obtained. The high speed system includes a 500Hz dual cavity laser and a camera that captures up to 1000 frames per seconds. The influence of an antithrombotic filter in the velocity field is evaluated.

9204-3, Session 1

Shape and 3D acoustically induced vibrations of the human eardrum characterized by digital holography

Morteza Khaleghi, Cosme Furlong, Worcester Polytechnic Institute (United States); Jeffrey T. Cheng, Massachusetts Eye and Ear Infirmary (United States); John Rosowski, Harvard Medical School (United States)

The eardrum or Tympanic Membrane (TM) transfers acoustic energy from the ear canal (at the external ear) into mechanical motions of the ossicles (at the middle ear). The acousto-mechanical-transformer behavior of the TM is determined by its shape and mechanical properties.

For a better understanding of hearing mysteries, full-field-of-view techniques are required to quantify shape, nanometer-scale sound-induced displacement, and mechanical properties of the TM in 3D. In this paper, full-field-of-view, three-dimensional shape and sound-induced displacement of the surface of the TM are obtained by the methods of multiple wavelengths and multiple sensitivity vectors with lensless digital holography. Using our developed digital holographic systems, unique 3D information such as, shape (with micrometer resolution), 3D acoustically-induced displacement (with nanometer resolution), full strain tensor (with nano-strain resolution), 3D phase of motion, 3D directional cosines of the displacement vectors can be obtained in full-field-of-view with a spatial resolution of 3 million points on the surface of the TM and a temporal resolution of 15 Hz. Also, due to time-varying nature of the TM, a novel, unique method based on multiplexed holography is developed to minimize the measurements time. In this method, the TM is illuminated simultaneously by three incoherently-superimposed pairs of reference and object beams, such that 3D components of displacement of the TM at each stroboscopic phase are obtained from only one single frame of the camera. Representative results showing 3D sound-induced displacement of the TM excited at different tonal frequencies are shown.

9204-4, Session 1

High-speed holographic system for full-field transient vibrometry of the human tympanic membrane

Ivo Dobrev, E. J. Harrington, Worcester Polytechnic Institute (United States); Jeffrey T. Cheng, Massachusetts Eye and Ear Infirmary (United States); Cosme Furlong, Worcester Polytechnic Institute (United States); John Rosowski, Massachusetts Eye and Ear Infirmary (United States)

Understanding of the human hearing process requires the quantification of the transient response of the human ear and the human tympanic membrane (TM or eardrum) in particular. Current state-of-the-art medical methods to quantify the transient acousto-mechanical response of the TM provide only averaged acoustic or local information at a few points. This may be insufficient to fully describe the complex patterns unfolding across the full surface of the TM. Existing engineering systems for full-field nanometer measurements of transient events, typically based on holographic methods, constrain the maximum sampling speed and/or require complex experimental setups.

We have developed and implemented of a new high-speed (i.e. > 40K fps) holographic system (HHS) with a hybrid spatio-temporal local correlation phase sampling method that allows quantification of the full-field nanometer transient (i.e. > 10 kHz) displacement of the human TM. The HHS temporal accuracy and resolution is validated versus a LDV on both artificial membranes and human TMs. The high temporal (i.e., <24us) and spatial (i.e., >100k data points) resolution of our HHS enables simultaneous measurement of the time waveform of the full surface of the TM. These capabilities allow for quantification of spatially-dependent motion parameters such as modal frequencies, time-constants and acoustic delays, which can be used to infer local material properties across the surface of the TM. The HHS could provide a new tool for the investigation of the auditory system with applications in medical research, in-vivo clinical diagnosis as well as hearing aids design.

9204-5, Session 1

Dynamic measurement of the corneal tear film with a Twyman-Green interferometer

Jason Micali, John E. Greivenkamp, College of Optical Sciences, The Univ. of Arizona (United States); Brian C Primeau, University of Arizona (United States)

This paper presents an interferometer for measuring dynamic properties of the in vivo tear film on the human cornea. The system is a near-infrared instantaneous phase-shifting Twyman-Green interferometer. The laser source is a 785 nm solid-state laser that has been carefully designed and calibrated to ensure that the system operates at eye safe levels. Measurements are made over a 6 mm diameter on the cornea. Successive frames of interferometric height measurements are combined to produce movies showing both the quantitative and qualitative changes in the topography of the tear film surface and structure for periods of up to 120 seconds at 28.6 frames per second. Several human subjects have been examined using this system, demonstrating surface height resolution of +/-25 nm and spatial resolution of 6 µm. Examples of features that have been observed in these in preliminary studies of the tear film include: post-blink disruption, evolution, and stabilization of the tear film; tear film artifacts generated by blinking; tear film evaporation and break-up; and the propagation of foreign objects in the tear film. This paper discusses the interferometer design, data reduction and analysis, and presents example results from in vivo measurements.

9204-6, Session 2

Artifact-free calibration of spatial carrier interferometry

Bradley T. Kimbrough, Korbinian Prause, Erik Novak, 4D Technology Corp. (United States)

Spatial carrier interferometry is a well-known single frame wavefront phase measuring technique. In this technique a large relative tilt is placed between the test and reference beams producing a high frequency carrier fringe pattern which is modulated by the desired measurement wavefront. Implementation of spatial carrier interferometry is relatively easily accomplished on most advanced laser interferometers. Since it is a single frame technique, it provides robust vibration immunity, enabling measurements involving long paths or mechanically decoupled elements as well as metrology into vacuum chambers and overall environmental immunity. One of the major limitations of this techniques is the degradation in measurement accuracy resulting from the large wavefront tilt applied between the test and reference beams. As a result of the large relative beam angle, the test and reference beams do not follow exactly to same path through the interferometer, resulting in what is generally known as retrace error. In this paper an automated calibration technique is introduced which determines the retrace error in a measurement setup without the use of a calibration artifact. This technique works well when measuring both flat and spherical test surfaces. In both cases, the difference between the calibrated wavefront and the wavefront measured on-axis with a temporal phase shifting is less than .05 waves. This process allows nanometer-level measurement of precision optics even in difficult environments.

9204-7, Session 2

Absolute height measurement of specular surfaces with modified active fringe reflection photogrammetry

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Deflectometric methods have been studied for more than a decade for slope measurement of specular freeform surfaces through utilization of the deformation of a sample pattern after reflection from a tested surface. Usually, these approaches require two orthogonal direction fringe patterns to be projected on a LCD screen or ground glass and require slope integration, which leads to some complexity for the whole measuring process. In this paper we propose a mathematical measurement model for measuring topography information of freeform specular surfaces, which integrates a virtual reference specular surface into the method of active fringe reflection delfectometry and presents a direct relation between height and phase of the measured surface. This method only requires one direction sinusoidal fringe pattern to be

projected on a LCD screen, resulting in a significant reduction in capture time over established method. After the whole system has been pre-calibrated, the phase information of the virtual reference can be setup and used for post process. During the measurement process, the fringe patterns of the measured surface are captured by a CCD camera. The reference and captured phases can be unwrapped with a heterodyne technique and optimum frequency selection method. Based on this calculated unwrapped-phase and that proposed mathematical model, absolute height of the inspected surface can be computed. Simulated and experimental results show that this methodology can conveniently calculate topography information for freeform and structured specular surfaces without integration and reconstruction processes.

9204-8, Session 2

3D optical profilometry using a fiber optic Lloyd's mirror

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This study defines measurements of three-dimensional rigid-body shapes by using a fiber optic Lloyd's mirror. A fiber optic Lloyd's mirror assembly is basically a technique to create an optical interference pattern using the real light point sources and their images. The generated fringe pattern thanks to this technique is deformed when it is projected on an object's surface. The deformed fringe pattern containing information of the object's surface profile is captured by a digital CCD camera. The two-dimensional Fourier transformation is applied to the image, which is digitized using a frame grabber card. After applying a band-pass filter to this transformed data in its spatial frequency domain, the two-dimensional inverse Fourier transform is applied. Using the complex data obtained by the inverse Fourier transform, the phase information is determined. A phase unwrapping algorithm is applied to eliminate discontinuities in the phase information and to make the phase data continuous. Finally, the continuous data determines the depth information and the surface topography of the object. It is illustrated for the first time that the use of such a fiber optic Lloyd's system increases the compactness and the stability of the fringe projection system. Such a fiber optic Lloyd's system which provides an accurate non-contact measurement without contaminating and harming the object surface has a wide range of applications from laser interference lithography in nanoscale to macroscale interferometers.

9204-9, Session 2

An asymmetric polarization-based frequency scanning interferometer: design principle

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Usage of transparent objects has been increased with technological developments of optical structure in display industries and micro optical component in MEMS industries. Their optical characteristics highly depend on the materials and the micro structures. When the optical measurement methods are used for dimensional quality control in their manufacturing, polarization change problem causes the measurement difficulties due to low sensitivity to measurement signals and high sensitivity to noise signals.

Interferometry is one of the most promising optical surface measurement techniques. In conventional symmetric interferometers, as the intensities of the reflected lights from the reference mirror and the object are much different, it results in low contrast of interference fringes and low accuracy of dimensional measurement. In this paper, to solve this problem, an asymmetric PFSI (Polarization based Frequency Scanning Interferometer) is proposed using asymmetric polarimetric method. The proposed PFSI system controls the polarization direction of the beam using polarizer and wave plate with conventional FSI system. By controlling the wave plate, it is possible to asymmetrically modulate the magnitude of object beam and reference beam divided by PBS. Based on this principle, if target object consists of transparent parts and opaque parts with different polarization characteristics, each of them can be measured selectively. After fast Fourier transform of the acquired interference signal, the shape of object is obtained from OPD (Optical Path Difference) calculation process. The proposed system is evaluated in terms of measurement accuracy and noise robustness through a series of experiment to show the effectiveness of the system.

9204-10, Session 2

Dynamic shape measurements of rough surface with a two wavelength method

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The shape measurements of rough surfaces with non-destructive and contactless techniques can be interesting for some applications as biomedical, mechanical and artwork. Although many techniques have been used for shape measurements we will focus on the two wavelength method using Digital Speckle Pattern Interferometry (DSPI).

Spatial Phase Shifting techniques (SPS) has been used in order to multiplex the recording with each wavelength. By means of a Fourier Transform analysis the amplitude and phase of the object beam for each wavelength is obtained separately. The subtraction of the two phases produces a wrapped phase map which gives information about the shape. This wrapped phase map can be considered a contour line map for a synthetic wavelength, related to the two laser wavelengths.

Until now, for rough surface measurements, a sequential recording is required, repeating the acquisition for each wavelength. In this work we have developed a system using two lasers with very close wavelengths which allows the two recordings to be taken simultaneously and makes possible to analyse dynamic objects. The illumination beams are guided by fiber optic and combined with a coupler to ensure the same direction for both wavelengths. Fiber optics is also used for the reference beams. The appropriate location of the tips fibers allows a correct spatial multiplexing.

The technique has been applied to different materials. It has been seen that the fringes visibility depends on the material properties.

9204-11, Session 3

Advanced wave field sensing using computational shear interferometry *(Invited Paper)*

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With the advent of faster computer systems, alternative concepts of wave field sensing have been developed. These methods do not rely on classical interference patterns arising from superposition of the wave field under investigation with a known reference wave. They are based on numerically solving an inverse problem, where the recorded intensities are interpreted as an effect, which has been caused by an unknown wave field subjected to various manipulations.

A particularly interesting approach is Computational Shear Interferometry (CoSI), which allows for determining arbitrary wave fields from a set of shear interferograms. This enables to perform common interferometric measurement tasks, such as 3D-shape and deformation measurement, lens testing or quantitative phase contrast imaging by means of a shear interferometer. Since the shear setup has remarkable low demands regarding the coherence of light, it is possible to realize a number of

fascinating applications by means of CoSI, such as Digital Holography of rough surfaces using a fiber coupled light emitting diode, interferometric optical inspection by means of a matrix LCD display or numerical refocusing in Differential Interference Contrast (DIC) microscopy.

In this publication we give a brief introduction into the field of Computational Shear Interferometry. We discuss limitations of the method with respect to spatial and temporal coherence of the underlying wave field and present various numerical methods to recover it from its sheared representations. Finally, we show experimental results on lens testing, deformation measurement and quantitative phase contrast microscopy.

9204-12, Session 3

Simple setup for optical characterization of microlenses

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Scientific articles focusing on fabrication of microlenses evaluate usually their optical performances by techniques such as scanning electron microscopy, optical topography or profilometry. Indeed, the quality of the optical elements is strongly defined by their geometry. However, deriving the optical characteristics from the microlens shape requires using propagation algorithms. Then, we present a simple and intuitive method, based on the measurement of the intensity point spread function generated by the microlens. The setup is less expensive than common systems and does not require heavy equipments. since it requires only a microscope objective, a CMOS camera and a displacement stage. This direct characterization method consists in scanning axially and recording sequentially the focal volume. Our system can be slightly arranged for two different imaging cases: the first one consists in the investigation of focusing by a transmissive element and the second one is adapted to the characterization of reflective elements. The latter is applied for radius of curvature measurements. For both cases, the fixed imaging configuration allows rapid estimation of quality and repeatability of fabricated focusing optical components. In order to validate this method, the results are compared with traditional techniques.

9204-13, Session 3

Dynamic temperature field measurements using a polarization phase shifting technique

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A measurement system that is capable of grabbing three phase-shifted interferometric images instantaneously (or simultaneously) was developed for dynamic temperature measurement over a period of time. The system presented is based on polarization phase-shifting techniques, presented previously, with the addition of calibration procedures and digital fringe processing techniques in order to accurately measure temperature fields varying in time.

A commercial disposable lighter using butane as a fuel was used. The lighter was settled to obtain the minimum flame size possible and prepared to fix the amount of fuel flow during the experiment. The variation observed in the experiment corresponds to the temperature distribution in the region surrounding the flame. Temperature profile measurement was obtained analyzing the dynamic behavior at 8.3 fps in a period of time of 12 s.

The temperature field measurement is based on measuring the refraction index difference by solving the inverse Abel transform. The inversion of the Abel transform is solved with the information obtained by the fringe order localization of the deformed fringe pattern generated by the flame under study.

The implementations of normalization fringe procedures present the advantage of avoiding the use of phase gratings, and also the advantage of using only three interferograms for the analysis. The system is considerably simpler than previous proposals, showing a suitable alternative to implement in an industrial setting.

9204-14, Session 3

Speckle interferometry at 10 micrometers wavelength: a combined thermography and interferometry technique and its application in aeronautical nondestructive testing

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Speckle interferometry has been developed on the basis of CO2 laser (10 micrometers) and thermographic camera using a microbolometer array. The long wavelength allows to measure large deformations and is well immune against external perturbations, when compared to similar systems working at visible wavelengths. The final outcome is a mobile interferometer that can be used in field conditions. The technique is based on specklegram recording on the microbolometer array. The background of the specklegram is constituted by the thermal image of the object. Therefore the temperature is simultaneously recorded with the specklegram. Phase-shifting is then applied to separate the thermal and deformation components of the signal. This allows simultaneous observation of deformation and temperature difference when an object undergoes a given stress. This finds interesting application in non destructive testing where thermo-mechanical phenomenons are studied. We show several applications in characterization and detection of defects in aeronautical composite structures.

9204-15, Session 3

Comparison of phase retrieval techniques based on the transport of intensity equation using equally and unequally spaced plane separation criteria

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Quantitative phase retrieval techniques based on non-interferometric [1] principles have led to advances in several fields of technology [2,3]. The reason for this lies in the fact that these techniques allow visualizing and characterizing processes that would otherwise be hidden and not be revealed. Besides this, these techniques can overcome the problems related to interferometry [4]. An important example of these methods is the Transport of Intensity Equation (TIE) that relates the phase of an object to the intensity distribution in the Fresnel region [5]. In order to solve TIE, two aspects have to be fulfilled; the first is the axial derivative of the intensity that is calculated using a set of captured intensities along the propagation axis. TIE can be solved in terms of a Poisson equation [2], where an optimum calculation of the axial derivative is usually made with equally spaced planes, but recently proposed TIE variants [6] showed reconstructions with non-equally spaced planes as well. The second parameter to be defined is the Boundary Condition (BC), e.g. Periodic, Neumann, or Dirichlet BC [7], which has to be selected carefully because it affects the solver stability and could introduce numerical

artifacts. In this work, a systematic study of the BC for the equal spaced TIE and the non-equidistant TIE configuration is presented. The paper work is carried out by analyzing the error of the retrieved phase given by both solvers. This is done in order to identify the fundamental problems of both types of solvers, and thus, choose the most suitable parameters in which both solvers can retrieve the best phase. This analysis allows developing guidelines for an optimal choice of BC, and more importantly, gives a methodology that enables removing the artefacts that are a result of the chosen BC. The latter enables TIE based measurements for a wide range of practical situations, where the object under study exceeds the field of view and thereby violates the BC. The conclusions of this work are supported with numerical and experimental results.

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9204-16, Session 4

Adding baselines at the Navy Precision Optical Interferometer

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The Naval Precision Optical Interferometer is an astronomical optical interferometer operating near Flagstaff, Arizona. A joint program between the United States Naval Observatory, the Naval Research Laboratory and Lowell Observatory, it has historically been involved in space imagery and astrometry. More recent has pushed for the addition of more baselines. It is currently capable of co-phasing 6 elements, so the commissioning of additional baselines requires ease of use and reconfigurability. At the time of this publication, a seventh station has been added and the final commissioning work on an eighth and ninth station are being completed. These last two stations will increase the longest baseline to 435 meters. This paper discusses the work to date on adding these stations and provides details on increased capabilities.

9204-18, Session 4

Minimization of errors in measurement of the internal geometrie of pipeline caused by the optical profilometer wheels

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The knowledge of pipelines conditions in oil and gas industry is of paramount importance, this knowledge avoids possible ruptures and/ or unnecessary maintenance. Currently, the use of PIGs (Pipeline Inspection Gauges) to monitor pipelines is the most used method. The internal optical profilometer, conical triangulation system developed in LABMETRO-UFSC, is a measurement system of internal geometric of pipeline. The internal optical profilometer system is not immune to effects caused by irregularities, for example: severe corrosion, weld seams and kneading in the pipeline internal wall. This paper presents a development and evaluation of an algorithm to compensate the effects on the internal geometry measurements in pipes caused by the movements of wheel trains passing through irregularities. These effects are mainly caused by the displacement of profilometer optical axis of the pipeline original axis. As a first and simplified approach, a 2D algorithm model, simulating the irregularities of pipeline internal surface was carried out. An algorithm to minimize the effects caused mainly by the irregularities in pipeline internal surface was developed. For both, 2D and 3D models the algorithm was validated, firstly by computed simulation, then to validate the measurement system with acquired data. The algorithm was validate with the optical internal profilometer for pipelines of the 6" (152 mm). The obtained results with simulated and real data have showed satisfactory improvement, the algorithm has significantly minimized the effects caused by the measurements system.

9204-19, Session 4

Glass bottle inspection by using digital in-line holography

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In this paper, the novel technique for investigating the quality of glass bottle by using digital in-line holography (DIH) has been proposed. In our experimental setup, the collimated beam of short coherent laser diode with wave length of 635 nm incident on a glass bottle. Then, the image bearing reflected beam consisted of quality profile of the glass bottle has been separated by a beam splitter and then recorded on a CMOS camera. The experimental results and numerically reconstructed images show us the defects inside the glass bottle, which have been detected by DIH. In addition, to obtain the radius of curvature of a glass bottle, the narrow opaque line object has been inserted between the laser diode and the beam splitter. The line pattern image bearing beam reflected from the bottle curvature surface has been recorded and numerically reconstructed. The reconstructed distance, which provided the sharpest image, has been used to calculate the radius of the curvature of the bottle by the lens formula. Our technique may be used for glass bottle inspection in the glass bottle making industry.

9204-25, Session 4

Small pitch fringe projection method with multiple linear fiber arrays for 3D shape measurement

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3-D shape measurement systems by contactless method are required in the quality inspections of metal molds and electronic parts in industrial fields. A grating projection method with phase-shifting method has advantages of high precision and high speed. Recently, the size of a BGA (ball grid array) becomes smaller. So the pitch of a grating pattern projected onto the specimen should be smaller.

In conventional method, fringe pattern is projected using an imaging lens. The focal depth becomes smaller in the case of reduced projection. It is therefore difficult to project a grating pattern with small pitch onto an object with large incident angles.

Authors recently proposed a light source stepping method using a linear LED device. It is easy to shrink the projected grating pitch with a lens because this projection method does not use an imaging lens. The pitch of the projected grating depends on the width of the light source. There is a limit to shrink the projected grating pitch according to the size of the LED chip.

In this paper, a small pitch fringe projection method with multiple linear fiber arrays for 3D shape measurement is proposed. The width of the fiber array is one digit smaller than the width of the LED chip. The experimental result that the projected pitch was less than 500 ?m with large incident angles 45 degrees is shown.

9205-1, Session 1

Dynamic data driven bidirectional reflectance distribution function measurement system *(Invited Paper)*

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The bidirectional reflectance distribution function (BRDF) is a fitted distribution function that defines the scatter of light off of a surface. The BRDF is dependent on the directions of both the incident and scattered light. Because of the vastness of the measurement space of all possible incident and reflected directions, the calculation of BRDF is usually performed using a minimal amount of measured data. This may lead to poor fits and uncertainty in certain unmeasured regions of incidence or reflection. A dynamic data driven application system (DDDAS) is a concept that uses an algorithm on collected data to influence the collection space of future data acquisition. The authors propose a DDD-BRDF algorithm that fits BRDF data as it is being acquired and uses on-the-fly fittings of various BRDF models to adjust the potential measurement space. In doing so, the intent is to find the best model to fit a particular surface and the best global fit of that BRDF with a minimum amount of collection space.

9205-2, Session 1

Temperature-dependent BRDF facility

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Applications involving space based instrumentation and aerodynamically heated surfaces often require knowledge of the BRDF of an exposed surface at high temperature. Addressing this need, JHU/APL has developed a BRDF facility that features a multiple–port vacuum chamber, multiple laser sources covering the spectral range from the longwave infrared to the ultraviolet, imaging pyrometry and laser heated samples. The laser heating eliminates stray light from a furnace and, requires minimal sample support structure, allowing low thermal conduction loss to be obtained, which is especially important at high temperature. The goal is to measure the BRDF of ceramic-coated surfaces at temperatures in excess of 1000C in a low background environment. Most ceramic samples are near blackbody in the longwave infrared, thus pyrometry using a LWIR camera can be very effective and accurate.

9205-4, Session 2

Surface-Plasmon Field Controlled Quantum-Dot Light Absorption and Spontaneous Emission

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The self-consistent equations for coupled electromagnetic-field dynamics and quantum kinetics of electrons are solved numerically by iteration for a quantum dot above the surface of a metal in the presence of a surface-plasmon-polariton wave. By including the energy relaxation and optical dephasing on a microscopic level, our calculated results demonstrate the interband dressing effect on the absorption of the surface-polariton wave, as well as its field scattering, by the quantum dot. Our calculations also show an induced optical gain and a triply-split spontaneous emission peak resulting from the interference between an induced polariton field and the probe or self-emitted light field in such a strong nonlinear system.

9205-5, Session 2

Determination of the normalized surface height autocorrelation function of a two-dimensional randomly rough dielectric surface by the inversion of light scattering data

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We use phase perturbation theory to determine the physical parameters and the normalized surface height autocorrelation function $(W(|bxp|))$ of a two-dimensional randomly rough dielectric surface from experimental light scattering data. The expression given by second-order phase perturbation theory for the contribution to the mean differential reflection coefficient from the in-plane co-polarized light of s-polarization scattered diffusely from such a surface forms the basis of this approach. We assume a Gaussian (or, more generally, a stretched exponential) functional form for $W(|bxp|)$, with unknown parameters and determine the physical parameters of the system numerically using a minmization approach based on the Levenberg-Marquardt algorithm. The input scattering data used in our reconstructions are obtained from rigorous numerical solutions of the reduced Rayleigh equations for the scattering of light from two-dimensional randomly rough dielectric surfaces. The physical properties we calculate using this method are the transverse correlation length of the surface roughness, the rms height of the surface, and the dielectric constant of the scattering medium, when $W(|bxp|)$ is assumed to have a Gaussian form. When the stretched exponential form is assumed for $W(|bxp|)$, we determine an additional parameter to assign a more accurate form to $W(|bxp|)$. The reconstructions obtained by this approach are found to be quite accurate for weakly rough surfaces, when the transverse correlation length of the surface roughness is small compared to the wavelength of the incident light.

9205-6, Session 2

Robust categorization of microfacet BRDF models to enable flexible application-specific BRDF adaptation

Samuel D. Butler, Michael A. Marciniak, Air Force Institute of Technology (United States)

Since the development of the Torrance-Sparrow bidirectional reflectance distribution function (BRDF) model in 1967, several models for BRDF have been developed. One of the most popular classes of BRDF models is the microfacet model, where physical optics effects are neglected; the BRDF can then be expressed as the sum of three components: directional surface reflection, directional volumetric reflection, and perfectly diffuse (Lambertian) volumetric reflection. Previous attempts to categorize BRDF models have relied upon somewhat vague descriptors

not well-defined in the community, such as empirical, semi-empirical, and experimental. Our approach is to instead categorize BRDF models based on functional form. This categorization is based on: microfacet normal distribution, geometric attenuation term, directional volumetric term, Fresnel term (if present), and cross section conversion factor (if present). When cataloged in uniform notation, model categorization is more readily obtained and meaningful as relative model comparisons become more apparent. Several popular models are compared to a standardized notation for a microfacet BRDF model, including: Blinn-Phong, Ashikhman-Shirley, Torrance-Sparrow, Ward-Duer, Cook-Torrance, Sandford-Robertson, Beard-Maxwell, and others. This analysis results in a library of various facet distributions, geometric attenuation functions, and volumetric functions, allowing one to modify existing BRDF models as desired for a particular application (e.g., Cook-Torrance with a cosine lobe distribution). This library also allows one to create a flexible microfacet BRDF model where the distribution function, geometric attenuation, and volumetric component are independently driven by the material properties (e.g., a novel BRDF with cosine lobe distribution, Cook-Torrance geometric attenuation, and Beard-Maxwell volumetric reflection).

9205-7, Session 3

A sensitive optical probe for surface topography based on an optimized astigmatic method

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Surface topography is required for many kinds of industrial products, and its applications keep increasing, making the need for adequate control of surfaces and an understanding of surface topography measurements more important than ever.

In this paper, we presented a sensitive and cost-effective optical probe for surface topography. An astigmatic method used in the optical probe was optimized for submicron/nanometer resolution and monotonic characterization of focus error signal (FES). A home-made system based on this optical prob ewas also presented, and the measurement results of surface topography indicate great potential of applications in many industrial fields.

9205-8, Session 3

Development of nano-LTP measurement at SSRF

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A high accuracy slope profile measuring instrument, the nano-radian Long trace profiler (Nano-LTP) was recently development at SSRF for the large mirror surface shape testing of grazing incidence optical components in synchrotron radiation. As promotion of the previous LTP, the accuracy of new instrument are possible improved to 100nrad (rms) in one dimensional surface slope measuring for plane mirrors lengths up to 1 m. We present the feature analyzes of different sources of errors which provide the important reference to the physics and engineering design of the instrument. Appropriate solutions have been investigated to reduce the effect of errors due to optical scanning system, environmental temperature changes, and vibration. System theory, physical analysis and engineering structure design of the Nano-LTP are presented in this paper, experiments are also researched and the results analyzed.

9205-9, Session 3

Study of surface roughness of corroded metals using plastic optical fiber sensor

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The broad objective of this paper is to study the surface of the corroded metals by using proximity sensor which works on the principle of light scattering by objects. The present work proposes a simple low cost sensor design making use of plastic optical fiber. The sensor is insensitive to source fluctuation and can detect surface roughness of the metals. The average surface roughness of the sample in different concentrations of acidic medium has been studied using the sensor. The reflected light intensity from the surface of sample metals was collected and measured as a function of lateral distance to estimate the roughness of the surface. The result has been compared with the stylus measurements.

9205-10, Session 4

Diffusers, properties, and performance in BSDF *(Invited Paper)*

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The “Bi-Directional Scattering Function” BSDF of a diffuser depends on several parameters, such as surface properties, observational conditions and further.

This paper describes experimental activities to achieve a better understanding about the interaction between diffuser properties and performance with regards to its scattering behaviour. For this purpose a set of 24 diffusers (12 in transmission, 12 in reflection) with defined surface properties have been manufactured, i.e. mainly the roughness related parameter R_q with a value between 0.5µm and 3.2µm. These components were systematically investigated and BSDF measurements were performed in the “Absolute Radiometric Calibration Facility ARCF” at TNO Delft in the Netherlands, a unique setup for the characterisation and calibration of optical components for space applications. The achieved results show systematic patterns in the relation between surface property and performance in BSDF, however, our experimental results deviate from existing theoretical models, which predict a significant change in BSDF with only a slight variation in surface roughness. The measurements presented in this paper suggest a far lesser dependency and therefore indicate the neccessity of further development of existing theoretical models. The derived empirical model will provide an accordingly additional data base for such further developments.

Further discussions will include the accurate verification of surface properties and the interlink of BSDF performance to speckle generation on detectors.

9205-11, Session 4

Near specular scatter analysis method with a new goniophotometer

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Detailed reflectance analysis has become an important issue in concentrating solar power technology (CSP), where the reflector is a key component in the energy conversion process. Any deviation in the redirection of the sunlight towards the receiver reduces the efficiency of the CSP-System, which means a loss of money. While other

sources of error have already been well understood and evaluated, new and innovative reflector materials that sometimes display near specular scattering give rise to recent intensive research on a detailed characterization of their reflectance properties.

This paper presents a new instrument prototype which has been developed at the OPAC (Optical & Aging Characterization) Laboratory in Spain to measure near specular scatter and evaluate its impact on specular reflectance. The instrument design is a modification of a parallel goniophotometer that has first been proposed in 1992. Main components are: A mirrored spheroid to create an angular-to-spatial mapping of the BRDF coming from a mirror sample and a camera with fisheye lens to capture it in one image. A key feature allows the distinction of the high intensity specular peak and the low intensity scatter. The evaluation method creates the specular reflection as a function of the offset angle from the specular direction. Past publications revealed that the principle has its limitations for applications that require full hemispherical BRDF analysis. However, first measurements with the prototype on solar reflector materials indicate that the presented instrument design offers a significant advance in the near specular reflectance characterization for this specific application.

9205-12, Session 4

Low-frequency Raman spectra and the nanostructure of chalcogenide semiconductors As-Se-S and As-Se-Te doped with samarium

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Found that the Raman scattering (RS) of chalcogenide semiconductor materials As-Se-S and As-Se-Te at frequencies below 100 cm-1 consists of two parts: the first - where the intensity with increasing purity of up to 30 ÷40 cm-1 decreases (quasi-elastic scattering), the second - where there is a broad band with a maximum at frequencies of ~ 63 ÷ 67 cm-1 (boson peak - BP). No such provision in the respective crystals. The observed features are associated with relaxation and excess density of states of acoustic vibrations localized irregularities in nanometer-sized material. It is shown that the contribution of the different types of scattering in a low-frequency range depends on the degree of disorder in the material, which varies with the chemical composition and by doping.

The intensity of the BP depends on the degree of disorder in the material, and varies with the chemical composition and the degree of alloying. For un-doped As-Se-Te intensity greater than BP As-Se-S, but samarium doping leads to a decrease in its As-Se-Te and an increase in As-Se-S. This difference in the Raman spectra of the studied explained that in As-Se-Te dimensions of structural elements smaller than the As-Se-S. Elements of the small size of randomly oriented and increase the degree of disorder. Proper charged defects (D + and D-) to a high concentration of available As-Se-Te, randomly distributed in the amorphous matrix, also increase the degree of disorder. Influence of the additive compositions of samarium in chalcogenide glass has uneven nature: in the case of As-Se-S samarium as a reactive element makes contact with all the elements entering into it, resulting in the formation of new structural elements. These structural units form micro-inclusions in the amorphous matrix and chaotic settling increases the degree of disorder at the middle order. The addition of samarium in As-Se-Te is the weakening of BP, and at high concentrations near extinction. Such a change in the Raman spectrum is explained with the features of distribution of samarium ions in the amorphous matrix, occurring at low concentrations and an increase in the degree of crystallinity at high concentrations.

The observed features in the Raman spectra at frequencies below 30-40 cm- 1, which quasi-elastic scattering are attributed with relaxation movement. Relaxation contribution to the low-frequency region of the Raman spectrum of estimated value of the intensity at a frequency where the course goes into boson region, normalized to the maximum value of PB. It has been shown that the rate of relaxation processes depends on the size of the structural elements included in the amorphous matrix , as well as the availability of volumes; accelerated by decreasing the size and increasing the structural elements of availability. As a result of doping samarium relaxation contribution decreases in the As-Se-S, increases in the As-Se-Te, which are explained by the different behavior of samarium atoms in them. In the first case, as it has a reactive element effect cross linking and increase the dimensions of structural elements, and in the second - mainly accelerates crystallization and reduces the size of the structural elements.

9205-13, Session 5

Light propagation in phosphor-filled matrices for photovoltaic PL down-shifting *(Invited Paper)*

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Efficient transparent light converters have received lately a growing interest from optical device industries (LEDs, PV, etc.). While organic luminescent dyes were tested in PV light-converting application, such restrictions as small Stokes shifts, short lifetimes, and relatively high costs must yet be overcome. Alternatively, use of phosphors in transparent matrix materials would mean a major breakthrough for this technology, as phosphors exhibit long-term stability and are widely available. For the fabrication of phosphor-filled layers tailored specifically for the desired application, it is of great importance to gain deep understanding of light propagation through the layers, including the detailed optical interplay between the phosphor particles and the matrix material. Our measurements show that absorption and luminescent behavior of the phosphors and especially the scattering of light by the phosphor particles play an important role. In this contribution several experimental parameters are investigated: refractive index difference between transparent binder and phosphors, particle size distribution, and particle surface properties. Commercially available highly luminescent UV and near-UV absorbing µm-sized powder is chosen for the fabrication of phosphor-filled layers with varied refractive index of transparent polymer matrix, and well-defined particle size distributions. Solution-processed thick layers on glass substrates are optically analyzed and compared with simulation results acquired from CROWM, a combined wave optics/ray optics home-built software. The results demonstrate the inter-dependence of the layer parameters, prove the importance of careful optimization steps required for fabrication of efficient light converting layers, and, thus, show a path into the future of this promising approach.

9205-14, Session 5

Effects of baffle in integrating sphere on total luminous flux measurement

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The baffle in an integrating sphere was studied to see its effects on the total luminous flux measurement. Effects of three baffle properties – the reflectance of the back surface, size, and position of the baffle, were studied through the spatial correction factor. The results show that the following conditions would make the total luminoux flux measured closer to the accurate value: increasing the back surface reflectance,

increasing the baffle diameter, and decreasing the distance between photometer and the baffle. The reasons were due to the difference in the non-uniformity in the sphere that the baffle induced in each condition. Optimising these conditions can yield more accurate total luminous flux.

9205-15, Session 5

Obtaining the information of suspended rod-shaped particles by use of polarization measurements

Ran Liao, Tsinghua Univ. (China)

In this paper, we will present the results which can enable us to obtain the information of the suspended rod-shaped particles by use of polarization measurements. We will give the experimental results and our explanation model.

In the experiment, we suspend the rod-shaped particles (glass fibers) with water in a round glass beaker with a magnetic stirrer at the bottom, and illuminate the samples by the linearly-polarized light from a 532nm-laser source. Then we measure the polarization properties, that is, degree of polarization (DOP) of the suspended sample at the side scattering angles. We find that DOP changes as scanning the central areas above the magnetic stirrer, and changes differently when the incident light is on or off the central axis formed by the fluid dynamics.

We can explain and expect the phenomenon observed in the experiments by use of our model which consists of suspended infinitely-long cylinders. In the model, we assume the orientations of the cylinders changes according to the fluid dynamics of the stirred water. From the simulations based on the model, the scattered polarizations of the suspended particles are dominated by their orientations. The polarized light illuminates the different parts of the sample, which means the possible different orientation distributions of the cylinders, and then the according measured polarization changes.

In this paper, we will show our recent results about the polarization measurements of the suspended rod-shaped particles, which promises the potential of the polarization measurements to obtain the information the suspended rod-shaped particles.

9205-17, Session 5

Uncertainties in strain measurements with birefringence

José G. Suárez-Romero, Instituto Tecnológico de Querétaro (Mexico)

Birefringence is a strain measurement method extensively used. It can be a reference to validate numerical calculation of strain distributions, however we need to evaluate errors and uncertainties to know the method reproducibility in order to compare with numerical calculation. As a first approximation strain depends of the material optical constant and of the wavelength. Therefore the material optical constant uncertainty is a first limitation of the method, a second is the resolution of the wavelength measurement. In this work we present an evaluation of the errors and sources of uncertainties of the birefringence method for strain measurements.

9205-33, Session 5

Measurement of spatial coherence through the shadows of small obscurations

Katelynn A Sharma, James K. Wood, Miguel A. Alonso, Thomas G. Brown, Univ. of Rochester (United States)

We present a simple method to measure the spatial coherence of a partially coherent field by analyzing measurements of the radiant intensity with and without a small, well-characterized obscuration. From these measurements, the coherence of the field can be estimated simultaneously for all pairs of points whose centroid is the same as that of the obstacle. By scanning the obstacle over the test plane, one can recover the full four-dimensional coherence function. It is shown that this approach is free of some of the limitations of alternative approaches (such as Shark-Hartmann systems), consisting of the use of apertures rather than obscurations, which are unable to measure correlations over point separations larger than the apertures' width. In principle, the measurements proposed here can be performed without any refractive or diffractive elements, allowing for measurements to be done in higher frequency regimes. In the experimental results presented here, however, the radiant intensity was measured at the back-focal plane of a lens. Our results are highly consistent with theoretical predictions for obscurations whose size is on the order of the coherence width of the source.

9205-18, Session 6

Modeling stray light from rough surfaces and subsurface scatter *(Invited Paper)*

James E. Harvey, Photon Engineering LLC (United States)

Over the years we have developed an adequate theory and understanding of surface scatter from smooth optical surfaces (Rayleigh-Rice), moderately rough surfaces with paraxial incident and scattered angles (Beckmann-Kirchhoff) and even for moderately rough surfaces with arbitrary incident and scattered angles where a linear systems formulation requiring a two-parameter family of surface transfer functions is required to characterize the surface scatter process (generalized Harvey-Shack). However, there is always some new material or surface process that provides non-intuitive scatter behavior. The linear systems formulation of surface scatter is potentially useful even for these situations. In this paper we will present empirical models of several classes of materials (subsurface scatter) or surfaces that allow us to accurately model the scattering behavior at any wavelength or incident angle from limited measured scatter data. In particular, scattered radiance appears to be the natural quantity that exhibits simple, elegant behavior only in direction cosine space.

9205-19, Session 6

Wave-optics simulation of partially coherent beam illumination scattered from perfectly-reflecting rough surfaces

Mark F. Spencer, Santasri Basu, Milo W. Hyde IV, Michael A. Marciniak, Air Force Institute of Technology (United States)

When using active-illumination systems for directed-energy and remote-sensing applications, more often than not a highly coherent laser beam propagates from the source through the atmosphere resulting in partially coherent beam illumination on the target. Interestingly enough, not much literature exists pertaining to the scattering of partially coherent light from rough surfaces. In an effort to bridge this gap, this paper develops a wave-optics simulation approach to the problem at hand. Specifically, the analysis uses two separate phase screens. The first phase screen is located in the source plane and accounts for the size and coherence properties of the incident illumination. Through multiple phase-screen realizations and far field-field propagation from the source plane to the target plane, the first phase screen allows for the generation of spatially partially coherent beam illumination with a Gaussian Schell-model (GSM) form. The second phase screen is located in the target plane and accounts for the surface parameters, i.e., the surface height standard deviation and correlation length. Through multiple phase-screen realizations in the target plane and far field-field propagation to the observation plane, the second phase screen accounts for the interaction of the incident GSM beam with a perfectly reflecting rough surface. This allows for the formulation of the average scattered irradiance and normalized autocorrelation function in the far field. Initial results show that this wave-optics simulation approach compares well with a previously validated 2D scalar-equivalent solution [Hyde et al., Opt. Express 21, 6807 (2013)].

9205-20, Session 6

Scattering models for range profiling and 2D-3D laser imagery

Gérard Berginc, Thales Optronique S.A.S. (France)

In security operations or medical imaging the main challenge is a need for fast identification, which is possible with a laser range profiler or 2D-3D laser imagery. This paper discusses modeling and simulation for High Temporal Resolution Ladar (Laser Detection and Ranging) and 2D-3D imagery. The design of high temporal resolution ladar, 2D-3D laser imaging systems requires accurate modeling software that will take surface reflectance representation as an input, and combine this representation with geometrical models to develop the scattering model of the objects illuminated by the laser wave of the active system. We obtain the surface reflectance of the objects by using the second order small-slope approximation for polarized incident laser wave. The randomly rough surfaces of the complex object are characterized by electromagnetic parameters (effective permittivity...) and roughness parameters (standard deviation of rough surface height and autocorrelation function).We discuss the modeling of nanosecond laser pulse scattering from objects with randomly rough surfaces. We show the range profiles at near infrared wavelengths have desirable stability with observation angle. In the second part of the paper we describe a simulation of 2D and 3D laser imaging. The physics based model is designed to provide accurate results but to also include the Mueller matrix, which gives the polarization states of the scattered waves from the complex objects. Our model addresses also transparent structures.

Examples of simulation of 1D, 2D and 3D laser signatures are presented in this paper.

9205-21, Session 7

3D laser imaging for concealed object identification *(Invited Paper)*

Ion Berechet, SISPIA (France); Gérard Berginc, Thales Optronique S.A.S. (France); Stefan Berechet, SISPIA (France)

This paper deals with new optical non-conventional 3D laser imaging. Optical non-conventional imaging explores the advantages of laser imaging to form a three-dimensional image of the scene. 3D laser imaging can be used for three-dimensional medical imaging, topography, surveillance, robotic vision because of ability to detect and recognize objects. In this paper, we present a 3D laser imaging for concealed object identification. The objective of this new 3D laser imaging is to provide the user a complete 3D reconstruction of the concealed object from available 2D data limited in number and with low representativeness. The 2D laser data used in this paper come from simulations that are based on the calculation of the laser interactions with the different interfaces of the scene of interest and from experimental results. We show the global 3D reconstruction procedures capable to separate objects from foliage and reconstruct a three-dimensional image of the considered object. In this paper, we present examples of reconstruction and completion of three-dimensional images and we analyze the different parameters of the identification process such as resolution, the scenario of camouflage, noise impact and lacunarity degree.

9205-22, Session 7

IR-imaging-based system for detecting the defects of conductive materials

Kimmo K. Leppänen, Juha M. Saarela, Tapio E. J. Fabritius, Univ. of Oulu (Finland)

Uniformity of conductive materials is an important property measured during manufacturing and in final products, especially in electronics applications such as organic solar cells. Differences in uniformity are often very small, invisible or below the surface of the sample. Therefore they are not always detectable even with high-resolution imaging systems. Electrical conductivity measurements are not limited to the visual detection of uniformity differences, but as it is not imaging the sample, it measures conductivity mainly between the measuring probes. To measure small uniformity differences in a large area, the area can be divided into many small area measurements, however this is time consuming. In practice, electrical conductivity standardized measurements are done by measuring some small areas of the sample, for example, by using four point probes. However, when the measurements do not cover the whole sample, they do not represent the absolute uniformity of the sample. To bypass the described limitations, a simple heating and IR-imaging based system was designed and was demonstrated with conductive materials. Samples with different defects were used to investigate the correlation of conductance and defect positioning. The utilized system is capable of localizing small defects in large-area samples using a single IR-image. This is a significant advantage from the manufacturing process measurement point of view.

9205-23, Session 7

3D measurement of both front and back surfaces of transparent objects by polarization imaging

Florence Drouet, Christophe Stolz, Olivier Laligant, Olivier Aubreton, Univ. de Bourgogne (France)

We present a method to recover the 3D shape of both external and internal surfaces of smooth transparent objects, such as glass windows or bottles. We use a combination of two methods known for the 3D reconstruction of specular surfaces: shape from distortion and shape from polarization. As each transparent surface reflects and transmits incident light, one can see two shifted images by observing the reflection of a pattern on two surfaces nearby. These images must not overlap, which prevents the use of dense pattern. In our application, we use a lightning made of an array of point source to enforce the separation of the two reflections. Looking at the reflection of one point source on the external surface with a calibrated camera, one can determine the depth and the orientation of this surface up to a one dimensional space of solution. The ambiguity is lifted by using the degree of polarization of the reflection, which depends on the incidence angle. Supposing that the external surface is locally flat, we show that there is the same ambiguity between position and orientation for the reflection coming from the internal surface. This ambiguity is lifted by using ray-tracing and Mueller calculus. So our method enables to measure both the position and the orientation of the two surfaces of a transparent object. We validate our method with an experiment on a transparent planar plate, and obtain an accuracy of 0.2 degree for the orientation and 0.6mm for the position of both surfaces.

9205-24, Session 7

Cone beam x-ray luminescence tomography reconstruction with prior anatomical information

Pei-An Lo, Meng-Lung Lin, Shih-Chun Jin, Jyh-Cheng Chen, Syue-Liang Lin, C. Allen Chang, Huihua K. Chiang, National Yang-Ming Univ. (Taiwan)

X-ray luminescence computed tomography (XLCT) is a novel molecular imaging modality that reconstructs the optical distribution of x-ray-excited phosphor particles with prior informational of anatomical CT image. The prior information improves the accuracy of image reconstruction. The system can also present anatomical CT image. The optical system based on a high sensitive charge coupled device (CCD)

is perpendicular with a CT system. In the XLCT system, the x-ray was adopted to excite the phosphor of the sample and CCD camera was utilized to acquire luminescence emitted from the sample in 360 degrees projection free-space. In this study, the fluorescence diffuse optical tomography (FDOT)-like algorithm was used for image reconstruction, the structural prior information was incorporated in the reconstruction by adding a penalty term to the minimization function. The phosphor used in this study is Gd2O2S:Tb. For the simulation and experiments, the data was collected from 16 projections. The cylinder phantom was 40 mm in diameter and contains 8 mm diameter inclusion; the phosphor in the in vivo study was 5 mm in diameter at a depth of 3 mm. Both the errors were no more than 5%. Based on the results from these simulation and experimental studies, the novel XLCT method has demonstrated the feasibility for in vivo animal model studies.

9205-3, Session PMon

Preliminary design of multi-spectral BRDF measurement system for water surface

Eunsong Oh, Korea Institute of Ocean Science & Technology (Korea, Republic of) and Yonsei Univ. (Korea, Republic of); Hyukmo Kang, Korea Institute of Ocean Science & Technology (Korea, Republic of); Sug-Whan Kim, Yonsei Univ. (Korea, Republic of); Youngje Park, Korea Institute of Ocean Science & Technology (Korea, Republic of)

Bidirectional reflectance distribution function (BRDF) is a fundamental parameter to describe the reflectance properties of measurement target in ocean remote sensing application. Conventional ways to measure BRDF of relatively small sample are usually to use single wavelength laser and detector combined with goniometer. However, in the ocean remote sensing field, BRDF value should be measured the reflected radiance from the water surface and spectral variation. In this paper, we report that a multi-spectral bidirectional reflectance distribution function (BRDF) measurement system have been developed with simplified goniometer and spectrometer. A hemi-spherical structure is adjustable to control an incident angle and detection fiber position after reflected from water surface. The system, which consists of NIST standard lamp and reference spectrometer covering from 360nm to 1100nm with 1.6nm spectral resolution, could be used for the target volume size having 30 – 50cm diameter and 30cm depth. The zenith angle limit of detecting fiber range from 15 to 75 deg, and the azimuth angle, relative to the illumination direction, range from 0 to ?180 deg with 5 deg step angle. The measured BRDF for water target having different suspended sediment value is compared with the remotely sensed data.

9205-25, Session PMon

Light scattering by aerosol particles and air in the molecular condensation nuclei (MCN) detector

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We study the light scattering by aerosol particles and air in the molecular condensation nuclei (MCN) detector, as well as the sensitivity of the photo detector of the photometer. MCN method is based on the conversion of impurity molecules to condensation nuclei of much larger size followed by the nuclei enlargement in the supersaturated vapor of specially selected low-volatile organic substances and detection of produced aerosol particles using an optical (nephelometric) method. The theory of light scattering by small aerosol particles, which dimension is commensurable with optical radiation wave-length, is based on Mie's theory. The interference nature of light scattering by aerosol particles is established and is found to be comparable (in order of magnitude) with the scattering of light by air in the photometer. The sensitivity of the photometer can be increased by more than an order of magnitude due to optimization of the optoelectronic part of the photometer. The detection threshold for the target component of the gas analyzer is attained at the spontaneous ionization background level and not at the limiting sensitivity level of the photo detector.

9205-26, Session PMon

Absolute testing for noncircular flats in synchrotron radiation

Hao Wei Lin, Li Song, Shanghai Institute of Applied Physics (China)

absolute flatness measurements by interferometry are classically three-flat tests, which compare two by two in the course of four or more tests. It is obvious that three flats are equivalent in various analytical methods that are not appropriate for noncircular flat testing, such as hexagonal, elliptical, rectangular and square flats. In this paper, a modified method for calibrating the noncircular optical flat surface in synchrotron radiation is proposed with the uncertainty analysis. The novel method is described in terms of functions that are symmetric or asymmetric only with respect to reflections at y axis. Absolute deviations of the noncircular flat could be obtained when mirror asymmetric errors are removed by N-position rotational average method. The formulas are derived for measuring the absolute surface errors of the noncircular flat, and experiments on high precision rectangular flat are performed to verify the method which is compared with the measurement results obtained by Zygo three-flat application.

9205-27, Session PMon

Intermediate field measurement to characterize the wavefront of high-power laser large optics

Stéphane Bouillet, Frédéric Audo, Commissariat à l'Énergie Atomique (France)

The French Laser MégaJoule (LMJ) is a high power laser project, dedicated to fusion and plasma experiments. It will include 176 square beams involving thousands of large optical components. The wavefront performances of all those optics are critical to achieve the desired focal spot shape and limit the hot spots that could damage the components. The CEA has developed experimental methods to qualify precisely the quality of the large optical components manufactured for the project and measure the effect of various defects.

For specific components, classical techniques like interferometric setups fail to measure the wavefront highest spatial frequencies (> 1 mm-1). In order to improve the measurements, we have proposed characterization methods based upon a laser beam diffraction interpretation. They present limits and we need to improve the wavefront measurement for high spatial frequencies (> 1 mm-1).

We present in this paper the intermediate field measurement based upon the Talbot effect theory and the Fourier analysis of acquired intensity images. The technique consists in a double pass setup: a plane wave is transmitted through the component twice, to simplify the setup and improve the measurement. Then, intensity images are acquired at different distances with a CCD camera and lead to the wavefront Power Spectral Density.

First of all, we describe the experimental setup to measure the wavefront of large specific components. Then, we show experimental results. Finally, we discuss about the advantages and the limits of such a method, and we compare it with our previous measurement methods.

9205-28, Session PMon

Investigation of interaction of structured illumination with randomly inhomogeneous surfaces

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This work is devoted to the use of different configurations of optical vortices in the diagnostics of rough and diffuse surfaces. Using the equations of scalar diffraction theory, we consider the propagation of an optical vortex, generated on a diffractive optical element. The algorithms for simulating the processes of propagation of spiral wavefronts in free space and their reflections from surfaces with different roughness parameters are discussed. The given approach is illustrated by the results of numerical simulations. The statistical study of amplitudes of zeros of a field reflected from rough surface was carried out. The relationship between surface roughness and speckle structure arising as a result of scattering of structured radiation with different parameters was studied.

9205-29, Session PMon

A Mach-Zehnder interferometer for the fine control of the polarization status of a beam

Enrico Tessarolo, Alain J. Corso, Consiglio Nazionale delle Ricerche (Italy); Paola Zuppella, Sara Zuccon, Maria G. Pelizzo, IFN-CNR LUXOR Lab. (Italy)

An optical system for the generation of a beam with a variable and controllable polarization status has been designed, realized and tested. The system is based on an interferometric set up, consisting of a spliting system, a phase delay system and a recombination system.

By controlling the optical path, it is possible to obtain every polarization status: linear, elliptical and circular. The system can be realized with an all-reflective scheme and it can work in a wide spectral band of the electromagnetic spectrum, from the near-infrared down to the extreme ultraviolet. The system can be integrated in different optical setups in order to enhance their versatility, such as in laser devices, optical instrumentations, synchrotron lines or of free electron lasers beam transport system. Finally It can be also used to test optical device and for calibration of optical components.

9205-30, Session PMon

A multifunctional automated system of 2D laser polarimetry of biological tissues

Natalia I. Zabolotna, Kostiantyn O. Radchenko, Vinnytsia National Technical Univ. (Ukraine)

One of the promising developments of optical biomedical systems of polarization diagnostics is the development of 2D laser polarimetry automated systems of microscopic images of biologic tissues.

2D laser polarimetry system of biologic tissues with enhanced functional capabilities is proposed. It consists of a semiconductor laser, quarter-wave plates, collimator optics, a polarizer and an analyzer, a microlens, a research sample and a CCD camera connected to the computer. The system implements 2D Stokes polarimetric mapping and 2D Mueller matrix mapping methods of optically thin (?<0.1) biological layers with the information selection of orientation-phase structure of biological tissue layers previously developed by the authors. It is given along with statistic, correlation and fractal analysis of obtained images.

The developed optoelectronic 2D Mueller matrix tomography and the tomogram analysis scheme are the most general implementation of the research principles and anisotropy reproduction of planar biological tissues. It implements the opportunities of polarization reproduction of the structure of biological tissue birefractional layers in the form of coordinate distributions obtained in two ways ? indirectly in the form of “orientation”, “orientation-phase” and “phase” Mueller matrix tomograms; directly in the form of birefractional index maps, “orientation” and “phase” maps.

The system also allows to obtain a complex of objective indexes which characterized by 2D polarization reproduced distributions under the following criteria: histograms of the distributions; statistical moments of the 1st - 4th order; autocorrelation functions; correlation moments; power spectra logarithmic dependencies of the distributions; fractal dimensions of the distributions; spectra moments.

The results of Mueller matrix tomography for the multilayer muscle biological tissue with attenuation coefficient ?≤0,75 and geometrical thickness of the layer 2 ?m are also presented. The 3th and 4th statistical moments and 4th correlation moment are diagnostically effective.

9205-31, Session PMon

Transmission of UV/visible light through model human epidermis at varying ambient humidity

Carlton W. Farley III, Sandra Sadate, Aschalew Kassu, Anup Sharma, Alabama A&M Univ. (United States)

Model human epidermal samples are used for transmission measurements at varying ambient humidity. Light is used from four different light emitting diodes (LEDs), of UVA wavelength of 365nm, and three visible wavelengths of 460nm, 500nm, and 595nm. A humidity-controlled chamber was used to house the samples while transmission measurements were taken. Many different types of measurements were taken, including raising ambient humidity from 20% to 75% then adding 0.5mL of water to the sample; lowering humidity from near 100% to 60%; and alternately raising and lowering of the ambient humidity. The results show higher transmission of light through the samples at very high ambient humidity, about 100%; whereas the transmission is much lower at lower ambient humidity. A simple model of epidermis as a turbid medium and reduced light scattering by refractive index matching is used to explain the results. Implications of these results are discussed.

9205-32, Session PMon

Scattering by three-dimensional slit-shape curves

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We analyze the scattering field generated by the coherent illumination of a three-dimensional transmittance characterized by a slit-shape curve. Generic features are obtained by using the Frenet-Serret equations which allows a decomposition of the scattering field. The analysis is performed by describing the influence of the curvature and torsion on osculating, normal and rectifying planes. Focusing and bifurcation effects are predicted and corroborated experimentally.

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9206-1, Session 1

A new optical head tracing reflected light for nanoprofiler

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High accuracy optical elements are applied in various fields. For example, ultraprecise aspherical mirrors are necessary for developing third-generation synchrotron radiation and XFEL (X-ray Free Electron LASER) sources. In order to make such high accuracy optical elements, it is necessary to realize the measurement of aspherical mirrors and with high accuracy. But there has been no measurement method which simultaneously achieves these demands yet. So, we develop the nanoprofiler that can directly measure the any surfaces figures with high accuracy. The nanoprofiler gets the normal vector and the coordinate of a measurement point with using LASER and the QPD (Quadrant Photo Diode) as a detecter. And, from the normal vectors and their coordinates, the three-dimensional figure is calculated. In order to measure the figure, the nanoprofiler controls its five-motion axis numerically to make the reflected light enter to the QPD's center. The control is based on the sample's design formula. Until now, under the condition that the QPD is fixed, the nanoprofiler has measured the difference the reflected light spot from the QPD's center, and led the real sample's figure from the difference. In this case, the measurement result includes some errors caused from the QPD's spatial irregularity of sensitivity. Now, in order to improve this, we contrive a new optical head which moves the QPD with using the piezoelectric actuator to make the reflected light spot be on the QPD's center continuously. We measure concave mirror using the nanoprofiler with the new optical head, and evaluate the measurement results.

9206-2, Session 1

The developmental long trace profiler (DLTP) optimized for side-facing optics at the ALS

Ian Lacey, Nikolay A. Artemiev, Edward E. Domning, Wayne R. McKinney, Gregory Y. Morrison, Simon A. Morton, Brian V. Smith, Valeriy V. Yashchuk, Lawrence Berkeley National Lab. (United States)

The autocollimator and moveable pentaprism based DLTP [NIM A 616 (2010) 212-223], a low-budget, NOM-like profiler at the Advanced Light Source (ALS), has been upgraded to provide fast, highly accurate surface slope metrology for long, side-facing, x-ray optics. This instrument arrangement decreases sensitivity to environmental conditions and removes the gravity effect on mirror shape. We provide design details of an affordable base tool, including clean-room environmental arrangements in the new ALS X-ray Optics Laboratory with advanced temperature stabilization and turbulence reduction, that yield measurements in under 8 hours with error less than 0.08 microradians (rms) for super polished, 880 mm flat optics. Repeatability is demonstrated better than 40 nanoradians (rms), limited mainly by the trace positioning and performance of the autocollimator. This work was supported by the U. S. Department of Energy under contract number DE-AC02-05CH11231.

9206-4, Session 1

Upgrade of surface profiler for x-ray mirror at SPring-8

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The key issues of optics used in third-generation synchrotron radiation and X-ray free-electron laser are how to handle the coherent x-rays. The shape error of a deflecting flat mirror should be controlled less than 10 nm along the length of the surface in order to preserve wavefront. The origins of the shape error are considered as fabrication error, gravitational and clamping deformation. Therefore surface profile in real condition such as reflecting direction and mounted state should be evaluated.

We have upgraded long trace profiler (LTP) of SPring-8 in order to measure side-facing surface. The gravitational effect on surface profile has been estimated from the difference between profiles measured in side-facing and up-facing condition. Comparative measurements using LTP and Fizeau interferometer in upward-facing condition were carried out. We will report results on surface measurement of x-ray optics at SPring-8.

9206-5, Session 1

Fabrication method of ellipsoidal mirrors for hard x-ray focusing-precision surface profiler and precision processing machine

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The purpose of this study is an establishment of a fabrication method of ellipsoidal mirrors for hard x-ray nano-focusing. Elliptical mirrors with an accuracy of a few nanometers in the Kirkpatrick-Baez geometry is commonly used as nano-focusing optics for analytical applications in synchrotron radiation facilities, because ellipsoidal mirrors, which can produce a point focus with a mirror, are difficult to manufacture in comparison with elliptical mirrors. Here, we developed a precision surface profiler and a precision processing machine for the ellipsoidal mirrors. The developed interferometric profiler can stitch sub-aperture data on the basis of relative angle between the neighboring shots. We obtained repeatability of 0.8 nm (RMS) using an ellipsoidal mirror. The processing equipment is developed for both a removal process of surface roughness and a computer-controlled shape correction. This demonstrated the improvement of surface roughness to ~0.2 nm (RMS), and the shape correction with several nanometers height resolution.

9206-6, Session 1

Design consideration for nano-accuracy long trace profiler at BSRF

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The third generation synchrotron radiation source like Beijing Advanced Photon Source (HEPS, Beijing) requires X-ray optics surface with high accuracy. It is crucial to develop advanced optics surface metrology instrument. The Long Trace Profiler (LTP) is an instrument which measures slope in the long dimension of an optical surface. In order to meet the accuracy requirements for synchrotron optics, a number of researches have been carried out to improve the LTP during the last decades. Many variations have been installed worldwide. As a part of the advanced research of HEPS, the metrology laboratory in BSRF (Beijing Synchrotron Radiation Facility) has been conducting work of building a new LTP since 2012. The accuracy of the instrument is expected to be <0.1?rad rms for component up to 1m in length. In this paper, we present the improved design of LTP, which can deal well with the random

noise and system errors happened in LTP-II and pp-LTP. The main characteristics of the profiler including short light path and precision optics reduce error caused by laser beam's lateral motion. The random noise and systematic errors is studied by numerical simulations. The results are considered as an important instruction for the proper choice of each component in the profiler. We expect to bring the profiler into operation in 2015.

9206-7, Session 2

A reflectometer for at-wavelength characterization of XUV-reflection gratings

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In our institute a technology centre for production and characterisation of highly efficient precision gratings is established. Within this project a new reflectometer for at-wavelength characterisation of the fabricated blazed gratings has been developed and produced. This new chamber complements our SR-based metrology instrumentation, namely the existing reflectometer [1] and the polarimeter/ellipsometer chamber for polarisation studies on magnetic or non-magnetic samples [2].

The main feature of the new reflectometer is the possibility to incorporate real gratings with dimensions up to 300 x 60 x 60 mm3 into the UHV-chamber. The samples are adjustable within six degrees of freedom by a newly developed UHV-tripod system, and the reflectivity can be measured between 0 and 90 degrees incidence angle for both s- and p-polarisation geometry. A variety of detectors will be accessable with a high dynamic range of at least 10 orders of magnitude.

The reflectometer is coupled permanently to a new optics beamline [3] on a BESSY-II bending magnet operating in the UV, EUV and soft x-ray range with the polarisation adjustable to either linear or elliptical. It will be available by the end of 2014.

Financial support of the European Community is gratefully acknowledged (ERDF-contract no. 20072013 2/43)

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9206-8, Session 2

At-wavelength metrology of x-ray optics at Diamond Light Source

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Modern third-generation synchrotron radiation sources provide coherent and extremely bright X-ray radiation beams; whose successful exploitation depends to a significant extent on the quality and performance of the optics employed on the beamlines. The quality of the beam delivered to the sample is limited by the imperfections and misalignment of the optics employed. This issue has become even more critical with the increasing use of active optics on the beamlines on one hand, and with the desire to achieve diffraction-limited and coherence-preserving beams on the other. In recent years, significant progress has been made to improve the optics testing and optimization techniques, especially the ones using X-rays for so-called at-wavelength metrology. These in-situ at-wavelength metrology methods can be used not only to optimize the performance of X-ray optics, but also to correct and minimize the collective distortions of upstream beamline optics, e.g. monochromator, windows, etc. An overview of the at-wavelength metrology techniques implemented at the Diamond Light Source will be given. These include grating interferometry and X-ray near-field speckle based techniques. Representative examples of the application of these techniques will also be given – including in-situ at-wavelength calibration and optimization of active bimorph mirrors, characterization of KB mirrors, and testing of non-reflective optics like FZP and CRLs.

9206-9, Session 2

Material and shape properties of the compound refractive lenses

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The synchrotron radiation sources of the third generation are the powerful research tool in the many areas of science and technology. In the near future new fourth generation synchrotrons are coming with unprecedented beam brilliance and thus coherence. In addition the existing third generation synchrotrons (ESRF, SPring-8, and APS) unveil plans for new storage rings that will increase the brightness of the photon beam 30 times higher than at present. Various hard X-rays methods of diagnostics (10÷100 keV) have a great potential for investigation of the structures and materials at nano-scale. Therefore, the possibility to obtain and control the beam with the submicron resolution by the X-ray optics is of interest. Compound refractive lenses (CRL) with a parabolic shape allow focusing the X-rays in the submicron spot with a focal length less 10 cm.

This work presents the results of the shape profile studies for CRL with the various radius of curvature (50, 200 and 500 microns) obtained by X-ray tomography, scanning electron microscopy with the 3D reconstruction option, and replica-profilometry. It should be noted that the profile characterization of CRLs with the small radius of curvature (R = 50 mm ÷ 500) presents some difficulties. In addition, we report the results of the investigations of the Be properties used as a material for CRLs and windows. Experiments were performed using inline scheme of X-ray microscopy and small-angle scattering at ID06 station of the European Synchrotron Radiation Facility (ESRF). The obtained results demonstrate that the material internal structure strongly influence on the x-ray homogeneity of the x-ray optical elements.

9206-10, Session 2

A ptychographic phase retrieval method for measuring figure error profile of soft x-ray focusing mirror

Takahiro Saito, Takehiro Kume, Hiroto Motoyama, Hidekazu Mimura, The Univ. of Tokyo (Japan)

The ellipsoidal mirror is a promising optical device in soft X-ray ranges because it can focus soft X-rays to nanometer dimension achromatically. We have been developing the fabrication process consisting of the mandrel fabrication and the surface replication. Evaluation of the surface figure profile is also essential to the development. We developed a ptychographic phase retrieval method for determining the figure error of an ellipsoidal mirror, in which a He-Ne laser is utilized. The wavefront error can be transformed into the three dimensional figure errors. We successfully obtained the figure error profiles. In this presentation, we will show the performances of the experiment system.

9206-11, Session 3

Development of high-precision figure measurement system for x-ray optics using laser focus microscope

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X-rays generated by a light source will be guided to the experimental apparatus using several x-ray optical devices, such as mirror optics, monochromators, refractive lenses, and so on. A mirror is one of the most widely used optical devices, and the surface shape of the mirror significantly affects the quality of x-rays at the sample position. Plane or nearly plane surfaces can be measured by, for example, using an interferometer and a slope profiler. However, focusing mirrors used for soft x-ray focusing and single nanometer hard x-ray focusing have minimum curvature radii of a few meters. It is difficult to measure the surfaces of these mirrors using conventional methods. We have been developing a new measurement system that uses a laser focus microscope as a probe for measuring steeply curved mirrors.

9206-12, Session 3

Stitching measurement of curved x-ray mirror with the new APS slope profiler

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The APS new slope profiler was designed to accommodate multiple sensors to cover a wide range of measurement needs [1]. The system is currently using an autocollimator as the slope sensor, similar to the NOM configuration [2]. The data acquisition system uses an EPICS interface that was developed in collaboration with the Advanced Photon Source Beamline Control Group. Measurements made on ultra-precise flat optics show that the new slope profiler performs close to the desired goal of 50 nrad rms [3].

Measurement of curved optics such as elliptical x-ray focusing mirrors is challenging due to the limited autocollimator angular range and the resulting systematic errors. One possible solution to mitigate this problem is to measure a series of overlapped segments of the mirror profile, then stitch the obtained sub-profiles using a computer code. In this way, the maximum angular span for each sub-measurement could be kept within the acceptable linear range of the autocollimator, thus improving the overall mirror profile measurement accuracy. In this paper, we present application to a Kirkpatrick-Baez elliptical mirror with a short focal length. The measurement procedure will be detailed, and the results we will compared with those obtained with a Fizeau interferometer and null lens.

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9206-13, Session 3

An extreme ultraviolet interferometer suitable to generate dense interference pattern

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It has been designed a new type of interferometer working in extreme ultraviolet (EUV) region and intended for direct imprinting of densest possible (for given wavelength) interference pattern into a substrate.

The interferometer belongs to the wave-front division category: each of its two aspheric mirrors reflects approximately one half of incoming laser beam and focuses it into a point image. Both focused beams have to intersect each other, and in the intersection region an interference pattern is generated. The closer the intersection region is to the above-mentioned point images, the smaller the interference field is, but simultaneously the smaller the fringe-pitch is.

The submitted paper describes interferometer design (inclusive fringe-pitch calculation, and inclusive design of multilayer reflection coatings for the wavelength 46.9 nm (Ar8+ laser) – ensuring equal reflectivity at different reflection angles). The interferometer design is supplemented not only by ray-tracing verification of straight shape of interference fringes in ideal interferometer, but also by modelling of interference pattern of real interferometer with various misalignments as well as with random deformation of mirrors. These data enable to define necessary production as well as alignment tolerances.

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9206-14, Session 3

Experimental results for absolute cylindrical wavefront testing

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Applications for Cylindrical and near-cylindrical surfaces are ever-increasing. However, fabrication of high quality cylindrical surfaces is limited by the difficulty of accurate and affordable metrology. Absolute testing of such surfaces represents a challenge to the optical testing community as cylindrical reference wavefronts are difficult to produce. In this paper, preliminary results for a new method of absolute testing of cylindrical wavefronts are presented. The method is based on the merging of the random ball test method with the fiber optic reference test. The random ball test assumes a large number of interferograms of a good quality sphere with errors that are statistically distributed such that the average of the errors goes to zero. The fiber optic reference test utilizes a specially processed optical fiber to provide a clean high quality reference wave from an incident line focus from the cylindrical wave under test. By taking measurements at different rotation and translations of the fiber, an analogous procedure can be employed to determine the quality of the converging cylindrical wavefront with high accuracy. This paper presents and discusses the results of recent tests of this method using a null optic formed by a COTS cylindrical lens and a free-form polished corrector element.

9206-15, Session 4

Pushing the limits: latest developments in angle metrology for the inspection of ultra-precise synchrotron optics *(Invited Paper)*

Tanfer Yandayan, TÜBITAK UME (Turkey); Ralf D. Geckeler, Physikalisch-Technische Bundesanstalt (Germany); Frank Siewert, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany)

The need for advanced angle metrology for inspecting the quality of synchrotron radiation (SR) optics is increasing continually. Due to the stringent demands on the form measurement of highly curved optical surfaces as well as of slightly curved optical elements of significant length, synchrotron facilities worldwide have been developing a new generation of highly accurate angle-measuring optical profilometers. Currently, the form measurement limits the fabrication of such optical surfaces. Thus the development of SR optics required for beamlines at the next generation of synchrotron sources like Free Electron Lasers (FEL) and Diffraction Limited Storage Rings (DLSR) necessitates the further improvement of the metrology. In this regard, improving the performance of angle measuring detectors like autocollimators is fundamental for achieving the 50 nrad rms residual slope deviation requirement as defined for future XFEL-optics.

A project called 'Angle Metrology' consisting of 16 worldwide partners and supported by European Metrology Research Programme was started in Sep 2013 in order to tackle the above issues. The project covers investigations on autocollimators under extremely challenging measuring conditions, ray-tracing models, 2D autocollimator calibration (for the first time worldwide), determination of error sources in angle encoders providing traceability by 'sub-division of 2π rad' with nrad uncertainty, angle generation by 'ratio of two lengths' in nrad level, and on the development of portable precise Small Angle Generators (SAGs) for regular in-situ checks of autocollimators' performance.

Highlights from the project will be reported in the paper and the community of metrology for X-Ray and EUV Optics will be informed about its progress and the latest work in angle metrology.

9206-16, Session 4

Angular calibration of surface slope measuring profilers with a bendable mirror

Nikolay A. Artemiev, Brian V. Smith, Edward E. Domning, Ian Lacey, Valeriy V. Yashchuk, Lawrence Berkeley National Lab. (United States)

Performance of state-of-the-art surface slope measuring profilers, such as the Advanced Light Source's (ALS) long trace profiler (LTP-II) and developmental LTP (DLTP) is limited by the instrument's systematic error. The systematic error is specific for a particular measurement arrangement and, in general, depends on both the measured surface slope value and the position along a surface under test. Here we present an original method to account for the instrument's systematic error in measurements with bendable X-ray mirrors. The idea of the method consists of extracting the systematic error from multiple measurements performed at different mirror bendings. An optimal measurement strategy for the optic, under different settings of the benders, and the method of accurate fitting of the measured slope variations with characteristic functions are discussed. We describe the procedure of separation of the systematic error of an actual profiler from surface slope variation inherent to the optic. The obtained systematic error, expressed as a function of the angle of measurement, is used for calibration of the instrument in actual conditions. This enables the optimal setting of bendable optics to the desired ideal shape with accuracy limited only by the experimental noise. Finally, accounting for the systematic error increases the accuracy of the measurements and allows measurements of highly curved optics with accuracy similar to those achieved with flat optics. This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

9206-17, Session 4

Design of a precision two-dimensional tip-tilting stage system for autocollimator-based long trace profiler angular calibration

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Autocollimator-based long trace profiler requires precise angular calibration to perform accurate measurements for x-ray mirrors. A prototype of a precision two-dimensional tip-tilting stage system has been designed and tested for a new autocollimator-based long trace profiler at the Advanced Photon Source (APS), Argonne National Laboratory (ANL). This flexural stage system is designed to meet challenging mechanical and optical specifications for producing high positioning resolution and stability for angular calibration for autocollimator-based long trace profiler. It could also be used as a precision mirror manipulator for hard x-ray nano-focusing with Montel mirror optics.

The mechanical design of a precision two-dimensional tip-tilting stage system as well as preliminary test results of its precision positioning performance are presented in this paper.

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9206-18, Session 5

A new x-ray optics laboratory (XROL) at the ALS: mission, arrangement, metrology capabilities, performance, and future plans *(Invited Paper)*

Valeriy V. Yashchuk, Nikolay A. Artemiev, Ian Lacey, Wayne R. McKinney, Howard A. Padmore, Lawrence Berkeley National Lab. (United States)

The X-Ray Optics Laboratory (XROL) at the Advanced Light Source (ALS), a unique optical metrology lab, has been recently moved to a new, dedicated clean-room facility that provides improved environmental and instrumental conditions vitally required for high accuracy metrology with state-of-the-art X-ray optics. The XROL serves several DOE labs that lack dedicated on-site optical metrology capabilities, including the Linac Coherent Light Source (LCLS) at SLAC and the LBNL's Center for X-Ray Optics (CXRO). The major role of XROL is to proactively support the development and optimal beamline use of x-ray optics. The application of different instruments available in the lab enables separate, often complementary, investigations and addresses different potential sources of error affecting beamline performance. At the beamline, all the perturbations combine to produce a cumulative effect on the performance of the optic that makes it difficult to optimize the optic's operational performance. Ex situ metrology allows us to address the majority of the problems before the installation of the optic at a beamline, and to provide feedback on design and guidelines for the best usage of optics. We will review the ALS XROL mission, lab design and arrangement, ex situ metrology capabilities and performance, as well as the future plans for instrumentation upgrades. The discussion will be illustrated with the results of a broad spectrum of measurements of x-ray optics and optical systems performed at the XROL. This work was supported by the U. S. Department of Energy under contract number DE-AC02-05CH11231.

9206-19, Session 5

An XUV optics beamline at BESSY II

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At the BESSY-II synchrotron radiation facility a new Optics Beamline is presently set into operation within the framework of our newly established grating production facility. It is coupled with a versatile Reflectometer as a permanent end station for at-wavelength characterization and calibration of the in-house produced precision gratings, mirrors, multilayered systems and novel nano-optical devices. The Plane Grating Monochromator (PGM) beamline operated in collimated light is equipped with an old SX700 monochromator, of which the blazed gratings (600 and 1200 l/mm) have been exchanged by new ones of improved performance produced in-house. Over the operating range from 10 to 2000 eV this bending magnet beamline has very high spectral purity achieved by (1) a four-mirror arrangement of different coatings which can be inserted into the beam at different angles and (2) by absorber filters for high order suppression. Stray light and scattered radiation is removed efficiently by in-situ exchangeable apertures and slits. Thus the new Optics Beamline together with the new versatile reflectometer is a powerful metrology tool for XUV reflectivity measurements in s- or p-polarisation geometry with linearly or elliptically polarised light on large samples up to 300 mm length and 4 kg weight. The setup will go into operation in 2014.

Financial support of the European Community is gratefully acknowledged (ERDF-contract no. 20072013 2/43)

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9206-20, Session 5

Fabrication of OSAKA mirror for synchrotron applications

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We, JTEC, have been fabricating OSAKA MIRROR using EEM, nano-fabrication, and RADSI and MSI, nano-measurements, developed by Osaka University [1], and have delivered nearly 200 Super Precision Mirrors to synchrotron radiation facilities worldwide.

We will give an overview of our production technologies and the potentialities. In addition, we will report some focusing results using our OSAKA MIRRORs installed in SPring-8 and SACLA [2][3]. Furthermore, we will show fabrications of challenging mirrors which are developed in collaboration with Osaka University and SPring-8.

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9207-4, Session PMon

Saw-tooth refractive lens for high energy x-ray focusing

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Saw-tooth refractive lenses (SRL) provide an attractive option for focusing of synchrotron X-rays because of their simple tunability. Focal distance can be changed simply by tilting the lens engaging more teeth. At Sector 1-ID at the APS, these lenses are used to efficiently focus high-energy X-rays. Two half lens can be used to focus in one direction. An additional orthogonal pair can be used to focus in two dimensions.

In this paper, we report on the analysis, design, and testing of a set of SRLs for high energy (>50 keV) X-ray focusing.

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9207-36, Session PMon

High-efficiency short focal diamond lenses: fabrication and performance

Lucia Alianelli, Diamond Light Source Ltd. (United Kingdom)

Diamond possesses many extreme properties that make it an ideal material for fabricating nanofocusing x-ray optics. Refractive lenses made from diamond are able to focus x-ray radiation with high efficiency & without compromising the brilliance of the beam. Electron-beam lithography and deep reactive-ion etching of silicon substrates have been used in a transfer-moulding technique to fabricate diamond optics with vertical and smooth sidewalls. Latest generation compound refractive lenses have seen an improvement in the quality and uniformity of the optical structures, resulting in an increase in their focusing ability. Synchrotron beamline tests of two recent lens arrays, corresponding to two different diamond crystalline morphologies, are described. Focal line-widths down to 210 nm, using a nanocrystalline diamond lens array and a beam energy of E = 11 keV, and 230 nm, using a microcrystalline diamond lens at E = 15 keV, have been measured using the Diamond Light Source Ltd. B16 beamline. The relatively high flux transmitted by these lenses, with a focal length f = 50 mm, is discussed in this paper. It is shown that further decrease of the focal length of diamond lenses is possible while still delivering good transmission. The influence of scattering from the lens material on the focusing properties is also discussed.

9207-37, Session PMon

X-ray harmonics rejection on 3rd-generation synchrotron sources using compound refractive lenses

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A new method of harmonics rejection based on X-ray refractive optics has been proposed. Taking into account the fact that the focal distance of the refractive lens is energy-dependent, the usage of an off-axis illumination of the lens immediately leads to spatial separation of energy spectrum by focusing the fundamental harmonic at the focal point and suppressing the unfocused high-energy radiation with a screen absorber or slit. The experiment was performed at the ESRF ID06 beam-line in the in-line geometry using an X-ray transfocator with compound refractive lenses. Using this technique the presence of the 3rd harmonic has been reduced down to 10-3. In total, our method enabled suppression of all higher order harmonics to five orders of magnitude using monochromator detuning. The method is well suited to third-generation synchrotron radiation sources and is very promising on the future ultimate storage rings.

9207-38, Session PMon

Diffractive focusing optics design at Helmholtz-Zentrum Berlin

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The Institute for Nanometre Optics and Technology of Helmholtz-Zentrum Berlin develops, fabricates and uses different X-ray diffractive optical elements. In accordance with the requirements of modern physical experiments, particular attention is paid to the design and fabrication of optical elements and gratings at total external reflection, with the linear size of the structure being up to one meter. We have developed an efficient software package to create a topology of these elements and simulate their behavior in real experimental conditions or analyze a possible result if technological errors occur during the manufacturing process. It consists of several parts and is operating with point source:

- the ZON software, to calculate the structure of an optical element in transmission and reflection;

- the KRGF software, to simulate the diffraction properties of an ideal optical element with point source;

- the DS software, to calculate the diffraction properties by taking into consideration material and shadowing effects.

Optional software allows simulation with a real non-point source. Zone plate thickness profile, source shape as well as substrate curvature are considered in this calculation.

Here, we also present the results of numerical calculations of a behavior of optical elements with topology required in real experimental conditions.

This work was supported by the Marie Curie FP7-Reintegration-Grants within 7th European Community Framework Program (project No. PCIG10-GA-2011-297905) and the BMBF project “Next generation instrumentation for ultrafast X-ray science at accelerator-driven photon sources” (project no. 05K12CB4).

9207-39, Session PMon

Polycapillary optics efficiency in focusing high-energy beams for micro-XRF

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Although X-ray fluorescence spectrometry (XRF) is a well studied technique for a while, it can still be a subject to technological improvements. XRF is widely used in many different fields, because of important features of the analysis such as non-destructive, often portable, fast and easy-use. It gives qualitative composition of analyzed sample and, through proper calibration and calculations (e.g. Fundamental Parameter method), can quantitatively determine the elements present in the matrix.

To have a better spatial resolution, various optical devices have been used in micro-XRF. Polycapillary optics represent one of the most recent and efficient development used in this field, as they allow very intense focused beams with respect to classical pinhole to be obtained. But this optics is known to be intrinsically low-energy band pass as the incident energy strictly influences the reflection angle, which defines the optics geometry.

Nowadays, the challenge is to optimize polycapillary lenses for high energy X-ray sources, in order to excite fluorescence K-lines above 20 keV, related to elements characteristics for various kinds of materials.

In this work, some preliminary studies on the characterization and optimization of focused beam coming from these lenses are presented. Then, some XRF spectra of gilded and enamelled silver standards, obtained with a classical 60 kV X-ray tube and with one combined with a focusing lens, are presented, in order to compare their efficiency in the excitation of Ag K-lines from the substrate and of Cd and Ba K-lines from the enamel.

9207-40, Session PMon

Measurement of the refractive index of nematic liquid crystals 5CB by means of x-ray interferometry

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In the present work the X-ray optical anisotropy of nematic liquid crystals (NLC) 5CB (4-pentyl-4'-cyanobiphenyl) has been investigated by use of X-ray (LLL) interferometer (silicon single crystal, reflection (110), MoK? radiation). During experiments has been studied anisotropy of 40 mkm thick NLC layer with planar alignment of molecules. The specimens are placed directly in the path of one of two interfering beams. In this way Moire fringes are obtained both in the absence and presence of specimens with different orientations of optical axes. The interference fringes obtained in this cases are shifted with respect to each other. The relative displacement of Moire fringes enabled us to observe and affirm at once the presence of X-ray optical anisotropy and to measure the values of refractive indices no and ne for this specimen (no is the refractive index for radiation with polarization normal to the principal plain, ne is that for radiation with lying in the principal plain parallel to the optical axis).

Thus, the X-ray optical anisotropy of NLC 5CB was observed using the proposed method and measured the values of refractive indices no and ne for specimen (the decrements for no and ne are ?o=1.33x10^-6 and ?e=8.16x10^-7 respectively). It was found out that NLC 5CB was X-ray anisotropic optically positive medium, (no–ne) < 0.

9207-41, Session PMon

Damage of EUV optical coatings induced by alpha-particles bombardment

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Future solar missions will investigate the Sun from very close distances and optical components are constantly exposed to low energy ions irradiation. Single layer thin films as well as extreme ultraviolet multilayer coatings have been exposed to low energy alpha particles (4keV). In order to change the total dose accumulated, for each ion fluency the time of exposure was varied. The experiment was carried out considering typical doses accumulated during the ESA Solar Orbiter mission. Results show that ion implantation affects the performances of both single and multilayer coatings.

9207-42, Session PMon

Novel space communication technology based on modulated x-ray source

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Radio frequency(RF) communication has been used in space satellite communications for decades and is still the workhorse for current space projects. Laser based optical communication is a hot topic recently because of its good security, relatively higher data rate, and small antenna size. However, bottlenecks such as the limited transmission distance, the wavelength dispersion during the transmission and mass SWAP burden (size, weight and power) on spacecraft are still major challenges, which restricts the future applications in deep space. A novel space communication method based on modulated X-ray source is presented in this paper. As a result of X-ray's short wavelength and great penetrability, a communication technology of long distance signal transmission in space can be achieved with smaller volume, lower weight and lower power. Therefore, X-ray communication (XCOM) is especially valuable to the deep space missions, which will be able to realize higher data rates, smaller SWAP than with RF and laser communications. High-speed modulation and high-sensitivity detection of X-rays are two major technical issues for the X-ray communication. A Grid-controlled Modulated X-ray tube (GMXT) is proposed and developed as X-ray transmitter. The communication signal is coded and applied to the modulated grid electrode, and then the corresponding X-ray signals are generated and sent out. X-ray detector based on micro-channel plate (MCP) is used as communication receiver because of its high temporal resolution. An audio communication experiment system based on XCOM is successfully demonstrated in laboratory including the X-ray transmitter and the receiver. The communication speed reaches 64 kilobits per second in a vacuum tube of 6 meters long. As a new concept of space communication, X-ray communication will have more important scientific significance and application prospects when technologies for X-ray modulation source, opttics and detection are further developed.

9207-43, Session PMon

Refractive optics x-ray microscopy as a multilayer structures investigation tool

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At the field of synchrotron instrumentation today more and more attention is paid to the development of nanofocused X-ray beam. The great advantage of such powerful tool – is the possibility of structures local investigation without optical reconstruction scheme and special preparation of samples. The most striking examples in this area are the study of the solar cells and research SOI heterostructures.

We studied two multilayer structures consisting of three pairs of alternating layers ZrOx/SiO2 with a thickness of 500 and 200 nm per each layer, respectively. The multilayer structures were manufactured by Ion Beam Deposition of corresponding stoichiometric target under high vacuum.

Multilayer structures were studied by X-ray Transmission Microscopy (XTM) and X-ray Scanning Transmission Microscopy (XSTM) techniques based on compound refractive lenses (CRL). All measurements were done at the ESRF ID6 beamline. Experimentally the 46 times magnified image together with the absorption contrast profile of the multilayer structure has been experimentally obtained. Based on the results, we conclude that the CRL based X-ray microscopy and X-ray microprobe are well suited for comprehensive study of multilayer structures, including the direct analysis of their interfaces.

9207-44, Session PMon

Thin film protective coatings for beryllium windows and lenses for synchrotron radiation sources

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Beryllium X-Ray optics – refractive lenses, filters and windows –are widely used at the synchrotron radiation sources. In addition, coming forth generation synchrotrons and X-ray Free Electron Lasers require the significantly improved properties of such optics in terms of surface quality and higher chemical resistance to the powerful X-Ray radiation. Nowadays, for preventing the destructive oxidation processes of Be optical elements they have mandatory blown on by inert gas.

In this paper we report a method for preventing oxidation of beryllium products by applying passivation coatings. As beryllium refractive lenses have a parabolic shape with the radius up to 50 ?m and minimum thickness between the parabola apexes up to ~10 ?m, the most suitable method for covering objects with a complicated shape is the atomic layer deposition (ALD). Al2O3 was chosen as a passivation material as it is a perfect diffusion barrier for oxygen. Structural properties, chemical state, thermal stability of the coated optics were investigated. In order to check the coatings to the powerful X-ray radiation, the samples were exposed in white beam at the ESRF ID 06 beamline. The very good adhesion of thin films on the sample was shown. Similar investigations with a larger exposure time were conducted in a monochromatic beam and showed no changes in the film oxygen concentration and the beryllium phase state. The experimental results allow evaluating the perspectives for the application of protective coatings Al2O3 produced by ALD to further reduce the safety requirements and simplifying the optical experimental schemes at synchrotrons.

9207-45, Session PMon

Focusing hard x-rays with tilted and wedged multilayer Laue lenses

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Multilayer Laue Lenses (MLL) are a relatively novel approach to focus especially hard x-rays effectively. Based on the principle of diffraction they will open a way to sub 10 nm and potentially down to 1 nm spot sizes. We have developed and demonstrated focusing of hard x-rays with 15.25 keV and 20 keV x-ray energy at the ESRF and PETRA III synchrotrons with pairs of crossed MLLs and focal sizes down to 39x49 nm. The individual lenses are prepared similar to TEM H-bar structures and two individual elements are finally glue bonded perpendicularly to each other with a lamella distance of less than 50 µm. The coherent diffraction microscopy method of Ptychography was used to identify the focusing capabilities of the lens system.

We have furthermore developed a method to produce wedged MLL with improved focusing efficiency compared to tilted geometry MLLs. This method allows fabricating the MLL layer stack independently from the actual tilting of the zones. A lens segment prepared from a specific deposition design can be processes to an element efficiently diffracting for different x-ray energies in wedged geometry. Using this manufacturing method we have demonstrated a lens, which showed significantly increased diffraction efficiency.

9207-1, Session 1

X-ray laminography and SAXS on beryllium grades and lenses and wavefront propagation through imperfect beryllium CRLs

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Hard X-ray free electron lasers provide fully transverse coherent x-rays. Though the natural divergence of SASE radiation is a few micro-radians, they still need to be collimated or focused while travelling up to 1km towards the sample. This can be done with beryllium compound refractive lenses (CRLs). Due to the coherence of the beam, it is important that the impurities or granular boundaries in these CRLs do not distort the wavefront of the x-ray beam to a measurable extend.
We measured the SAXS signal of various beryllium grades and of 2D parabolic lenses made of IF-1 beryllium. Then, we imaged these samples using X-ray computed laminography at a resolution of 1 micrometer. Computed laminography is a 3D imaging technique similar to computed tomography, but particularly adapted for flat extended samples.
These measurements are used to characterize the voids and granular boundaries in the beryllium samples. Boundaries between the former powder particles are easily seen for beryllium grades produced via sintering techniques. This is not the case for cast ingots. Common to all samples are voids with diameters in the 10 micrometer range as well as smaller sized, denser impurities. Finally, we use wavefront propagation simulations in order to analyze the effect of voids in the CRLs on the wavefront of the XFEL beam. If the distance “lens to focus and sample” is large enough, the diffraction patterns emerging from the voids smoothen out.

9207-2, Session 1

X-ray multilens interferometry based on planar refractive optics

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Recently it was shown that the concept of planar refractive x-ray optics can be used to develop new interferometry techniques in addition to focusing and imaging schemes. A bilens interferometer based on planar refractive optics has been proposed. It consists of two sets of identical planar parallel lenses. Two secondary coherent sources are arising under coherent illumination. Those sources generate a periodical interference pattern i.e. standing wave. The period of the standing wave depends on

observation distance and varies from tens of nanometres to tens microns. To extend a bilens interferometer beam acceptance we have developed a multilens system, which uses more than two parallel lenses. The increase of the beam acceptance leads to raising a contrast of the interference pattern at the expense of interference maxima narrowing. In comparison with the bilens interferometer, where the mechanism of a wave front formation is simple, a multilens system forms a more complicated interference pattern which can be described using Talbot imaging formalism. The aim of this work is to study multilens interferometer optical properties. The multilens structures were manufactured on Si substrates by the MEMS micro fabrication technology involving lithography and deep etching. The split distance between lenses is 30 um. Study of interferometer properties were performed in the energy range of 12-36 keV at ID6 and ID11 beamlines of the ESRF synchrotron. We believe that this new interferometry approach opens up new possibilities of developing precise X-ray nano-metrology and nano-diagnostic techniques.

9207-3, Session 1

Kinoform lenses for focusing high-energy x-rays (> 50 keV)

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High-energy x-rays (> 50 keV) from a synchrotron source are well suited for numerous applications, such as studies of materials structure and stress in bulk or extreme environments. Some of these methods require high spatial resolution. Linear kinoforms are shown to focus monochromatized undulator radiation in the 50 - 65 keV range down to 0.2 - 1 micron beam sizes at 0.25 - 1 m focal distances. These lenses were fabricated by reactive ion etching of silicon. At such high energies, these optics can offer enhanced transmission and lens aperture.

9207-5, Session 1

The high-resolution reciprocal-space mapping of the Si-Ge nano-heterostructure by refractive x-ray optics

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With increased interest to the nano and micro sized heterostructures, the high precision methods and techniques of their analysis are needed. One of the powerful instruments of studying such structures is an x-ray diffractometry. We propose to apply X-ray refractive optics as a wave front analyzer of diffraction pattern produced by nanocrystal arrays.

We performed a high resolution x-ray reciprocal space mapping of the Si-Ge nano-heterostructure by using compound refractive lenses as a Fourier transformer. The experiments were conducted at the ESRF ID06 beamline (Grenoble, France). The Si-Ge nano-heterostructure is 100 nm Ge nanocrystals on free-standing 90 nm wide and 150 nm high Silicon(100) pillars with a periodicity of 360 nm along the (110) crystal direction. These nano-heterostructures were realized on a Si (001) substrate using the CMOS gate spacer process.

The regions near the Si (400) and Ge (400) reflections were mapped. The 40 um undulator source size and 60 m optical path has enabled to achieve the angular resolution ~4 urad that is better than the angular resolution achievable by conventional triple-crystal diffraction techniques. We have achieved high dynamical range by using a beam stop, a proper exposure time and adaptive x-ray attenuators with 16-bit CMOS x-ray camera from Photonic Science.

Reciprocal space map provide the information about Si-Ge heterostructure orientation, periodicity, crystal structure and stress distribution in 3 dimensions. Received nano-heterostructure diffraction patterns were described in terms of kinematical and dynamical diffraction theory. The lateral Si-Ge heterostructure x-ray diffraction patterns were detected with the time resolution less than 1 second, which opens up new possibilities in nanocrystal dynamic observations.

9207-6, Session 2

Variable line spacing diffraction grating fabricated by direct write lithography for synchrotron beamline applications

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High resolution x-ray spectroscopy applications like Resonant Inelastic X-ray Scattering (RIXS) require diffraction gratings with ultimate characteristics. The gratings should have very high groove density and at the same time provide high diffraction efficiency. These are conflicting requirements for classical grazing incidence reflecting gratings since they can operate efficiently only at very shallow angles on incidence and diffraction. The problem can be solved by use of Multilayer Blazed Gratings (MBG) fabricated by deposition of x-ray multilayers on saw-tooth substrates, which can provide much higher efficiency at non-grazing incidence geometry. MBG parameters should be optimized in terms of requirements and constrains of design of a particular spectrograph to achieve high resolving power and high throughput of the whole tool. In this work we consider a compact RIXS spectrograph with two-dimensional imaging which is planned to be built at Advanced Light Source. The instrument utilizes a set of diffraction gratings, and each of them is optimized for a particular relevant absorption edge. Numerical simulation of diffraction efficiency show that optimized MBGs can have much higher efficiency as compared to grazing incidence gratings and provide required resolving power due to high groove density and high order operation. We discuss details of grating optimization as well as technological aspects of MBG fabrication. This work was supported by the US Department of Energy under contract number DE-AC02-05CH11231.

9207-7, Session 2

Specific aspects of roughness and interface diffusion in non-periodic Mo/Si multilayers

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Most of the currently used reflective coatings for EUV and X-ray mirrors are periodic nanometer multilayers. Depending on the number of periods and the absorption in the multilayer stack a certain band width of the incoming radiation can be reflected. In order to increase the integral reflectance or to accept larger ranges of incidence angles, non-periodic multilayers are needed. With the transition from periodic to non-periodic

multilayers new challenges arise for the deposition process. Since the reflectance spectra are sensitive to every single layer thickness a precise coating control and an exact knowledge about the interface reactions is required. Since interface interdiffusion is connected with a thickness contraction of the multilayer the diffusion induced thickness change has to be knowns very precisely. However, the specific contraction behavior depends on the roughness of the layers, the crystallographic microstructure and morphology, the layer thickness and the process parameters used in the magnetron sputter deposition process. Finally, we developed processes which result in single layers with microroughness below 0,1 nm. In addition with the application of tiny barrier layers at the multilayer interfaces we were able to create stable interfaces with known thickness contraction values independently on the Si and Mo layer thickness.

In our presentation we will report about the progress in the development of non-periodic multilayers and the recently obtained results of EUV reflectometry, TEM and AFM investigations.

9207-8, Session 2

In-situ stress study on WSi2/Si multilayers

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Multilayer Laue lenses (MLLs) were developed to focus hard x-rays with high efficiency to spot sizes of below 10 nm. MLL optics have demonstrated a line focus of 16 nm with 31% efficiency at 20 keV. A 2-D focus of 25x 40 nm2 (FWHM) with an efficiency of 17% at a photon energy of 19.5 keV was demonstrated using the MLL microscope at the Advanced Photon Source [2]. More recently, an 11.2 nm hard X-ray line focus (FWHM) with 15% efficiency was achieved via ptychography [3]. Thick multilayer depositions (>50 microns) are required for MLLs with large acceptance and correspondingly large focal length. However, thick multilayers contain more stress, which can lead to delamination, cracks, and internal defects during sectioning. We have reported our studies on accumulated stress during deposition of MLLs by changing deposition pressures [4-5]. Previous reports on the multilayer structure for an MLL were all based on a layer thickness ratio of 1:1. In this study, in-situ measurements on film stress during the growth of WSi2/Si multilayers with different layer thickness ratios are reported using a Multi-beam Optical Sensor (MOS). Stress was measured layer-by-layer as the multilayer was deposited. Results indicate that accumulated stress can be reduced by changing the thickness ratio of the two materials.

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9207-9, Session 2

Thermal expansion properties of thin multilayer films

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Under synchrotron radiation white beam exposure, strong mechanical stress can build up in multilayer optics, caused by the thermal mismatch between layer material and substrate material. To study the stability and performance of multilayer optics under heat load, Pd, Cr, and B4C single layers of thicknesses in the nanometer range and [Pd/B4C] multilayers were prepared in the sputter-depositing facility of the ESRF Multilayer Laboratory. Curvature changes versus temperature were measured using a Shack-Hartmann wave front sensor. Films coated on 200 micrometer thin Si wafers induced significant curvature changes over a temperature range from 40°C to 200°C. A combined parameter containing Young's modulus and the thermal expansion coefficient was defined to describe the thermal expansion properties. The investigation shows that all three materials in thin film cause less thermal expansion than expected from material properties for bulk material in the literature. In particular, the thermal expansion of B4C films appears to be close to that of the Si substrates.

9207-10, Session 3

Can a simple edge focus x-rays in two dimensions?

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When one considers to use a refraction process the answer can be yes! Already in 1949 Kirkpatrick [P. Kirkpatrick, J. Opt. Soc. Am. 39, 796-796 (1949)] showed that X-rays can be focused, when impinging onto a concave interface at very grazing angle of incidence. This phenomenon occurs in both possible beam paths, i.e. on entering a material through a curved interface as well as on exiting from the material through a curved interface. Now in an edge the beam successively enters and exits. Then, when the edge is rightangled, one just would have to curve both surfaces adjacent to the edge appropriately in the direction of the edge for independent focusing in the two orthogonal directions. Sanchez del Rio and Alianelli [M. Sanchez del Rio & L. Alianelli, J. Synchrotron Rad. 19, 366–374 (2012)] posed the question, which shape is needed for focusing an incident X-ray beam by use of a single concave interface. For an incident plane wave the first interface would need a hyperbolic profile, while the exit interface would have to have an elliptical profile. Obviously the angle of grazing incidence onto the first interface needs to exceed the critical angle for total reflection, while a similar limitation does not exists for exiting from the material.

This contribution will present the theoretical treatment and optimisation of the "focusing edge". In addition experimental data will be presented for a lithographically produced plastic slide, which distorted such that an edge presented concave spherical curvature in both directions. The transmitted beam was focused in this case in two dimensions as expected.

9207-11, Session 3

Flux monitoring by x-ray diffracting crystals under ambient air conditions

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The physical phenomena that can be used for monitoring x-ray flux on the optical elements include photoionization, photoemission and generation of non-equilibrium charge carriers. Although these are very well studied for a variety of optical materials, x-ray detection or monitoring of incident flux is usually performed using dedicated stand-alone detectors (e.g., solid state detectors, ionization chambers). Such practice is not always justified.

X-ray detection by voltage developed across a diffracting Si crystal (bulk response) was demonstrated in prior studies (e.g. [1]). Photoemission from diffracting crystals (surface response) was also extensively studied earlier (e.g. [2,3]).

In the present work, x-ray monitoring by optical elements will be discussed as a universal concept where various circuit configurations can be utilized to optimize charge collection and enhance sensitivity.

X-ray monitoring optical elements can offer a non-invasive way of monitoring incident flux, simplified alignment procedures and cost savings. There is no particular requirement on the brightness of the incoming radiation. Thus, x-ray monitoring optical elements can be used in optical arrangements with conventional sources such as x-ray tube [4].

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9207-12, Session 3

Diffractive 3-dimensional XUV optics at HZB: recent developments

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The 2-Dimensional and 3-Dimensional variable line spacing (VLS) gratings based on total external reflection give the unique possibility for spectroscopy and focusing in application to 4th and 5th generation synchrotron sources. We focus on the elaboration of novel approaches for design and fabrication of 3D VLS working in the entire energy range, from THz to hard X-rays [1-3]. These optical elements have unique combination of properties and can operate at all XUV sources including Free Electron Lasers (FELs) and High Harmonic Generators (HHGs).

Such 3D DOEs are able to cover the energy range of up to 20 keV with energy resolution ?/?? ≥ 1000 for soft x-ray and ?/?? ≥ 10000 for hard x-ray. We fabricate 3D VLS for time-resolved spectroscopy (energy range 100 – 2000 eV, 7500-9500 eV), FELs and ERLs (energy range up to 3 keV), and HHGs (energy range 10 – 200 eV).

Possible scientific fields of such optics application will be discussed also.

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9207-13, Session 3

X-ray coherence studies applied to capillary optics

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The rapid development in X-ray physics and instrumentation motivates the intense research in the field of X-ray radiation transmission by micro- and nanocapillaries that mostly used to design capillary/polycapillary optical elements.

The physics of polycapillary optics (known also as Kumakhov lenses) that represents a strictly ordered set of close-packed capillaries [1] is based on the principle of total external multiple reflection of high-energy photons from the inner surfaces of hollow waveguides. A number of useful applications of that optics could be analyzed within the ray optics approximation (see, for instance, in [2]). But our special interest in this work is in estimating the radiation propagation in such systems from the point of view of wave approach taking into account also the phase modulation at radiation developing down to the channels (surface X-ray channeling) [3,4]. Obviously, the possibility to handle the radiation coherence at its propagation in polycapillary optics opens new opportunities for various applications.

In this work, we will present a new developed computer code "CAPSYS" written in C++. This model allows calculating the characteristics of radiation passing through capillary structures. The results of recent studies on coherent X-ray radiation propagation in capillary structures with various both periodicity and diameters of the channel-guides. We have demonstrated the possibility to determine the parameters of the optics to essentially preserve high degree of coherence that undoubtly will be of growing interest for the researchers specializing in X-ray applications based on combination of coherent radiation sources with capillary/polycapillary optics.

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9207-14, Session 4

MagneDyn: the future beamline for ultrafast magnetodynamical studies at FERMI

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The future beamline MagneDyn will be devoted to study the electronic states and the local magnetic properties of excited and transient states of complex systems by means of the time-resolved X-ray absorption spectroscopy (TR-XAS) technique.

The beamline will use both the low and high energy sources at FERMI covering the wavelength range from 100 nm down to 1.3 nm. An on-line photon energy spectrometer will allow to measure the spectrum with high resolution while delivering most of the bean to the endstations. Downstream the beam will be eventually split and delayed, by means of a delay line, and then focused with a set of active KB mirrors. These mirrors will be able to focus the radiation in one of the two MagneDyn experimental chambers: the cryomagnet endstation and the Resonant Inelastic X-ray Scattering (RIXS) endstation. After an introduction of MagneDyn scientific case, we will discuss the layout in detail showing the expected performances of the beamline.

9207-15, Session 4

Ray tracing simulation of beamline 1-BM at the Advanced Photon Source for polarization analyses of synchrotron optics

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SHADOW software is a ray-tracing program for the simulation of optical systems of synchrotron radiation beamlines [1]. In most synchrotron facilities a large number of beamline optics have been designed and verified using the SHADOW program, including optical arrangements employing crystal optics. Beamline 1-BM was recently repurposed for optics and detector testing. Studies of different types of crystal optics including bent crystal analyzers for inelastic x-ray scattering are possible. In this paper, we present optical ray-tracing studies for test set-ups that take advantage of the polarization variation of the bending magnet radiation above and below the horizontal plane of the beamline.

[1] M. Sanchez del Rio, N. Canestrari, F. Jiang, and F. Cerrina, J. Synchrotron Rad. 18, 708 (2011).

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9207-16, Session 4

Optimisation of the beam transport system for experiments with small spots at the x-ray fluorescence beamline at Elettra

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This discussion regards the use of an X-ray monochromator for multi-purpose experiments based on a small spot at the sample in the photon energy range 2 - 14 keV. The example case treats a bending magnet source at the Elettra storage ring. In the experiment either high spectral resolution is to be supplied by use of diffraction crystals or high flux is to be achieved by use of multilayer coatings. The principal goal was the supply of a stationary exit beam employing a minimum amount of motions with minimum crosstalk into the remaining degrees of freedom. The problem could be solved by reducing the vertical beam displacement to a minimum, in this case of 6 mm. Then two facing and sufficiently long multilayer mirrors can be operated with parallel surfaces in the channel-cut mode, which is known from the operation of crystals. When the tuning is achieved by use of two crystals, the operation mode needs to be modified to a "pseudo" channel cut mode, as the separation between the crystals needs to be varied unavoidably. Here the required single translation is realised in a system using flexure hinges, which provide sufficient range while avoiding cross-talk to the very sensitive tilt and roll adjustment of the second crystal. The system remains rather compact with crystal lengths, which can remain below 70 mm, and mirror lengths, which are mostly smaller than 100 mm, respectively. Only in one out of 3 multilayer mirror channels one mirror measures 200 mm.

9207-17, Session 5

Preparation and characterization of x-ray mirrors with three single layers of a-C, B4C, and Ni onto one 800-mm long Si substrate

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Advanced research light sources such as free-electron lasers require ultra-precise and long x-ray mirrors that provide high reflectivity, high flux and a wide wavelength range. An x-ray mirror is a combination of a substrate and a coating [1]. The demand for large mirrors has increased during the last years, since surface finishing technology is now able to process longer substrate lengths on the rms-level of a few nanometers. A state-of-the-art x-ray mirror could be coated with more than one single layer to allow a selection of thin-film materials. At FLASH II, the improved and extented wavelength range will be 4-80 nm [2]. It is further expected that the photon beam will possess an average single pulse energy of 1-1000 µJ, a pulse duration of 10-200 fs (FWHM), a peak power of 1-5 GW. At the Helmholtz-Zentrum Geesthacht, an in-house designed magnetron-sputtering facility enables us to deposit single layers and multilayers on up to 1.5 m long substrates. Earlier results confirmed the excellent uniformity of x-ray optical coating properties in the tangential and sagittal direction of the mirrors [3]. Moreover, the deposition facility provides the simultaneous fabrication of two mirrors to achieve identical properties.

Thin films of amorphous carbon (a-C), boron carbide (B4C) and nickel (Ni) are deposited by means of magnetron sputtering. The thin-film properties were investigated and analyzed by means of x-ray reflectometry (XRR), atomic force (AFM), and interference microscopy. The experimental results will be analysed using simulations for the determination of layer thickness, density and roughness.

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[3] M. Störmer, F. Siewert, J. Gaudin, Development of x-ray optics for advanced research light sources. Proc. SPIE 8078 (2011) 80780G.

9207-18, Session 5

APS deposition facility upgrades and future plans

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The Advanced Photon Source (APS) has recently invested in the design and construction of a new linear deposition system intended for fabrication of multilayers and profile coatings. The two-cathode machine, which accommodates substrates up to 150 mm in length, includes provisions for lateral thickness gradient production. This machine incorporates a servo drive for velocity profiling as well as provisions for multilayers produced with reactive sputtering. Both of these capabilities are new to the APS. Design considerations, issues, and first results will be presented. An outlook on future upgrades to the other APS deposition equipment will be discussed.

9207-19, Session 5

Graded multilayers for fully polarization resolved resonant inelastic x-ray scattering in the soft x-ray range

Christian Morawe, Jean-Christophe Peffen, ESRF - The European Synchrotron (France); Ratchadaporn Supruangnet, Synchrotron Light Research Institute (Thailand); Lucio Braicovich, Politecnico di Milano (Italy); Nicholas B. Brookes, ESRF - The European Synchrotron (France); Giacomo Ghiringhelli, Politecnico di Milano (Italy); Flora Yakhou-Harris, ESRF - The European Synchrotron (France)

In the context of the ESRF upgrade programme, the former soft x-ray beamline ID08 has been closed and a new beamline is being rebuilt at the position ID32. One important technique will be resonant x-ray inelastic scattering (RIXS) done in the fully polarized mode i.e. with resolution in the linear polarization both of the incident and of the scattered beam. To this end a polarimeter will be inserted in the new RIXS spectrometer in order to measure simultaneously the energy spectra and the polarization. This approach is based on the results of preliminary work on the RIXS equipment at ID08.

The new instrument works between 500 eV and 1000 eV and requires graded multilayers to optimize the energy tunability and the polarization sensitivity. The present work covers the design, the fabrication, and the characterization of the multilayers. The depositions were carried out at the ESRF Multilayer Facilities using DC sputtering techniques. Particular emphasis is put on the generation of the correct d-spacing profile over the full coated area. Performance evaluations during test and commissioning experiments with soft x-rays and under realistic conditions complement the paper.

9207-20, Session 6

Phase characterization of attosecond multilayer mirrors: from EUV to soft x-rays

Franck Delmotte, Charles Bourassin-Bouchet, Sébastien de Rossi, Evgueni Meltchakov, Lab. Charles Fabry (France); Angelo Giglia, Stefano Nannarone, Consiglio Nazionale delle Ricerche (Italy)

Phase controlled multilayer mirrors provide an efficient solution to transport, focus and/or compress attosecond pulses in the extreme ultraviolet (EUV) domain (30-100eV). In this spectral range, one can access the spectral phase by measuring the photocurrent generated at the mirror surface as a function of the incoming photon energy. It has been already demonstrated that one can extract the spectral phase from such measurements under specific hypotheses.

We will present the experimental protocol for such measurements and discuss the validity of this technics in the EUV and in the soft x-ray domains. In the EUV spectral range, our experimental results are in good agreement with simulations and with attosecond metrology measurements. However, we will show that the previous hypotheses are no longer valid at shorter wavelengths, in the soft x-rays domain. This is mainly due to the fact that the electron mean free path becomes comparable to the individual layer thickness in the multilayer mirror.

We propose here a new method that allows to extend the validity of phase characterization using photocurrent measurements in the soft x-ray domain (100 – 500 eV). We will present the first experimental results concerning the phase characterization of Cr/Sc multilayer mirrors in the water window and compare these results with simulation.

9207-21, Session 6

Attosecond broadband multilayer mirrors for the water window spectral range

Alexander Guggenmos, Stefan Radünz, Roman Rauhut, Ludwig-Maximilians-Univ. München (Germany); Michael Hofstetter, Ludwig-Maximilians-Universität München (Germany) and Max-Planck-Institut für Quantenoptik (Germany); Sriram Venkatesan, Angela Wochnik, Christina Scheu, Ludwig-Maximilians-Univ. München (Germany); Eric Gullikson, Lawrence Berkeley National Lab. (United States); Stefan Fischer, Bert Nickel, Ulf Kleineberg, Ludwig-Maximilians-Univ. München (Germany)

Extending single attosecond pulse technology from currently sub-200 eV to the water window spectral range will provide new insight in ultrafast coreshell electron wavepacket dynamics especially of low-Z materials, as being measured by time-resolved spectroscopy as well as the investigation of biomolecules and cells in attosecond time-resolved soft x-ray microscopy. The demand on highly reflective multilayer mirrors for spectral shaping or focusing attosecond pulses in the water window wavelength range, between the K-absorption edges of carbon and oxygen (2.3-4.4 nm), manifests itself due to the lack of sources with sufficient photon flux. Spectral shaping of attosecond pulses can be realized by multilayer mirrors containing the amount of layers needed for fulfilling the pulse bandwidth requisite and for achieving sufficient reflectivity. Realizing this requisite requires interface-optimized multilayer mirrors with almost perfect interfaces due to the huge loss in reflectivity which arises from boundary imperfections. Here, we report about our achievements in minimizing the interface roughness of ion beam deposited Cr/Sc multilayer mirrors by optimizing the kinetic energy of the utilized Krypton ions both in the deposition and the assisted ion-beam interface polishing process. The characteristics of our ion-beam polished (sub-) nano layers are investigated using in-situ ellipsometry. Experimental results from measurements using X-ray reflectometry, spectral ellipsometry and XUV reflectrometry as well as TEM cross section images are shown and discussed.

9207-22, Session 6

Phase delay characterization of multilayer coatings for EUV short pulses reflectance

Alain J. Corso, Univ. degli Studi di Padova (Italy) and IFN-CNR LUXOR Lab. (Italy); Enrico Tessarolo, Consiglio Nazionale delle Ricerche (Italy); Paola Zuppella, Sara Zuccon, IFN-CNR LUXOR Lab. (Italy); Marco Nardello, Univ. degli Studi di Padova (Italy); Maria G. Pelizzo, IFN-CNR LUXOR Lab. (Italy)

The phase delay introduced by reflection on multilayer (ML) mirrors is an important feature in many fields such as attosecond pulses compression, photolithography or in pump and probe experiments performed with EUV short pulses. The experimental characterization of the ML phase delay can be obtained by the standing wave distribution measurement (by using Total Electron Yield (TEY) signal) combined with reflectance measurement. In this work, different ML structures with aperiodic capping-layers were designed, deposited and their reflectance and phase delay were characterized. The method adopted allows to retrieve the ML phase delay by using the TEY signals taken at different working configurations and it doesn't require the comparison with a bulk reference sample. The results obtained are presented and discussed.

9207-23, Session 7

Characterization of heated crystalline fluoride cut-off filters in the FUV

Kenneth F. Dymond, Scott A. Budzien, Andrew C. Nicholas, U.S. Naval Research Lab. (United States); Peter W. Walker, Computational Physics, Inc. (United States); Richard Eastes, Andre Krywonos, Robert Eppig, Florida Space Institute (United States)

Heated strontium fluoride and barium fluoride crystalline filters have long been used in spaceflight applications to set the short-wavelength cut-off of an instrument's passband. Current scientific needs for more compact imaging instruments to study the morphology, small-scale structure, and dynamics of the Earth's nighttime ionosphere have re-invigorated interest in this technique. Additionally, improved production techniques have resulted in higher purity crystals with improved performance. We report measurements, made in NRL's UV Calibration Facility, of the short-wavelength cut-off of the higher purity strontium and barium fluoride filters. The measurements are compared to the performance calculated from published optical constants. The measured transmittances as functions of temperature show that currently available materials perform better than materials produced less than a decade ago, making heated filters a more attractive means of determining the short-wavelength cut-off of an instrument.

9207-24, Session 7

Characterization of thin HPHT IIa diamond by transmission and reflection measurements

Shunji Goto, Hiroshi Yamazaki, Ayumi Miura, Yuichi Inubushi, Haruhiko Ohashi, Japan Synchrotron Radiation Research Institute (Japan); Makina Yabashi, RIKEN (Japan)

A single crystal diamond is used for various x-ray optics; x-ray monochromator, beam splitter, and phase plate at synchrotron radiation beamline. Due to the success of self-seeding at the LCLS in hard x-ray region, it is also becoming a crucial optics to produce seeded XFEL using delayed part of transmitted wave of thin diamond crystal. We have been characterized several thin HPHT IIa diamond crystals for self-seeding at SPring-8 Angstrom Compact free electron LAser, SACLA.

Sumitomo HPHT IIa diamond crystals were characterized using pseudo plane-wave setup at 1-km beamline of SPring-8. Si 111 double-crystal monochromator and Si 531 asymmetric collimator (b= -0.05) produce pseudo plane wave of 19.75 keV. Both reflection and transmission of 0.18-mm-thick (001) diamond was used. The rocking curve width of 400 symmetric Bragg-case reflection agreed well with calculated value of 3.6 micro-radians.

In this report, we will show the basic performance of transmittance and reflectivity, together with topographic images. Preliminary results will also be demonstrated for self-seeding done at 10 keV in SACLA BL-3.

9207-27, Session 8

Development of achromatic full-field hard x-ray microscopy with ultraprecise total reflection mirrors

Satoshi Matsuyama, Yoji Emi, Hidetoshi Kino, Yasuhisa Sano, Osaka Univ. (Japan); Yoshiki Kohmura, Tetsuya Ishikawa, RIKEN (Japan); Kazuto Yamauchi, Osaka Univ. (Japan)

We developed an achromatic and high-resolution full-field hard X-ray microscope with an advanced Kirkpatrick-Baez mirror optics, which consists of four total-reflection mirrors. The mirrors were fabricated to have a figure accuracy of 2 nm using elastic emission machining (EEM), microstitching interferometry (MSI) and relative-angle-determinable stitching interferometry (RADSI). For efficient observation, two additional elliptical mirrors as a condenser were placed just upstream of samples. The constructed microscope has a numerical aperture of 1.5 mrad and magnification of 658x and 214x in vertical and horizontal directions. The performance of the microscope was investigated using a Siemens star chart at BL29XUL of SPring-8 at an X-ray energy of 10 keV. As a result, the lines with width of 75 ~100 nm could be resolved. Lines wider than 100 nm could be clearly observed. Also, no chromatic aberration was confirmed by taking images over a wide energy range from 7 to 12 keV. The lines with width of 100 nm could be successfully resolved using the X-rays within the energy range. For practical demonstration, tungsten particles with diameter of 1 ~ 0.2 micron were observed using the X-ray absorption fine structure technique. X-ray absorption spectra over the imaged area were easily obtained.

9207-28, Session 8

Toward achromatic soft x-ray imaging system with sub-10 nm spatial resolution

Satoru Egawa, Takehiro Kume, Hidekazu Mimura, The Univ. of Tokyo (Japan)

The Wolter mirror has been a promising imaging device in X-ray microscopy fields due to excellent characteristics such as no achromatic aberration, large aperture and long work distance. Despite its long history, there is no Wolter mirror practically used for high resolution microscopy, because high figure accuracy is required on the surface. In this presentation, we will show the performances of a new manufacturing process developed for rotationally symmetric mirror including Wolter mirror. Then, this presentation includes optical simulations for designing soft X-ray imaging system aiming sub-10nm spatial resolution.

9207-29, Session 8

Development of optical components for METIS instrument

Marco Nardello, Univ. degli Studi di Padova (Italy); Sara Zuccon, Alain J. Corso, Paola Zuppella, IFN-CNR LUXOR Lab. (Italy); Giampiero Naletto, Univ. degli Studi di Padova (Italy); Silvano Fineschi, Ester Antonucci, INAF - Osservatorio Astronomico di Torino (Italy); Maria G. Pelizzo, IFN-CNR LUXOR Lab. (Italy)

The ESA mission Solar Orbiter (SOLO) is dedicated to the study of Solar Atmosphere and Heliosphere. As a part of the payload, the instrument METIS (Multi Element Telescope for Imaging and Spectroscopy) will provide images of the corona, both in the visible range and at the hydrogen Lyman-? emission line (121.6 nm). The realization of optical coatings able to reflect/transmit such spectral component is therefore necessary. Design and realization of optical components as well as tests in relevant environment are presented. In particular, custom designs will be described for high efficiency coatings and for filter able to transmit the 121.6 nm while reflecting the visible light; both of them based on Al and MgF_2. Testing of degradation due to harsh solar environment is described.

9207-30, Session 8

Hard x-ray monitoring for astrophysical applications

Ladislav Pina, Czech Technical Univ. in Prague (Czech Republic)

This work addresses the issue of the X-ray monitoring for astrophysical applications. The proposed wide-field optical system has not been used in space yet. A novel approach is based on use of 1D “Lobster eye” optics in combination with Timepix X-ray detector in energy range 3 - 40 keV. The proposed project includes theoretical study and functional sample of Timepix X-ray detector with multifoil wide-field X-ray “Lobster eye” optics. Optics focusing X-rays on a detector is the only solution especially in cases where the intensity of X-ray radiation is below the sensitivity of the detector, e.g. while monitoring astrophysical objects in space, or phenomena in the Earth’s atmosphere. The optical system could be used in a student rocket experiment at University of Colorado. Ideal opportunity is to extend the Cubesat of Pennsylvania State University with the hard X-ray telescope demonstrator consisting of optical module and Timepix detector.

9207-31, Session 9

Phase contrast imaging using a micro focus x-ray source

Wei Zhou, Keivan Majidi, Jovan G. Brankov, Illinois Institute of Technology (United States)

Phase contrast x-ray imaging, a new technique to increase the imaging contrast for the tissues with close attenuation coefficients, has been studied since mid 1990s. This technique reveals the possibility to show the clear details of the soft tissues and tumors in small scale resolution. A compact and low cost phase contrast imaging system using a conventional x-ray source is described in this paper. Tungsten K?1 line with the photon energy 59.3 keV was used for imaging. Asymmetrically cut germanium crystal was used as the beam monochromator. And symmetrically cut germanium crystal was used as the analyzer. The

details for designing the system are discussed. The method that was used to stabilize the system is introduced. A piece if chicken thigh bone was used as the sample. Some images obtained in this system are given. The image quality, image acquisition time and the potential clinical application are discussed.

Using the conventional x-ray source is of great importance, because it provides the possibility to use the method in hospitals and clinical offices. Simple materials and components are used in the setup to keep the cost in a reasonable and affordable range. High energy x-ray beam can be used in phase contrast imaging. Therefore the radiation dose to the patients can be greatly decreased compared to the traditional x-ray radiography.

9207-32, Session 9

Reflection on multilayer mirrors: beam profile and coherence properties

Alexander Rack, Christian Morawe, ESRF - The European Synchrotron (France); Lahsen Assoufid, Argonne National Lab. (United States); Reiner Dietsch, AXO DRESDEN GmbH (Germany); Frank Siewert, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Amparo Vivo, Peter Cloetens, ESRF - The European Synchrotron (France); Timm Weitkamp, Synchrotron SOLEIL (France); Lucia Mancini, Diego Dreossi, Sincrotrone Trieste S.C.p.A. (Italy); Eric Ziegler, ESRF - The European Synchrotron (France)

Compared with crystal lattice reflection, the use of Bragg reflection on a multilayer mirror as a monochromator for hard X-rays has the advantage of a higher photon flux density because of the larger spectral bandpass. The main disadvantage lies in the strong modulations in the reflected beam profile. This is a major issue for micro-imaging applications, where multilayer-based monochromators are frequently employed to deliver high photon flux density. A subject of particular interest is the origin of the beam profile modifications, namely the irregular stripe patterns, induced by the reflection on a multilayer. For multilayer coatings in general it is known that the substrate and its surface quality significantly influence the performance of such kind of mirrors as the coating reproduces to a certain degree roughness and shape of the substrate. This presentation shall outline that the mid-spatial frequency roughness (MSFR), from 1 mm-1 to 1 µm-1, of the multilayer substrate is of crucial importance for the beam profile modifications. A set of dedicated comparative experiments have been carried out, in which the influence of the finite X-ray source size, the surface profile as well as the surface roughness and the beamline geometry were studied.

9207-33, Session 9

Characterization of low contrast samples and fast processes by portable x-ray tomography

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In this paper a novel experimental set-up for studying low contrast samples and fast processes, through X-ray Tomography, is presented.

An imaging technique, based on the use of polycapillary optics, has been developed. Generally, the study of low contrast samples and fast processes, like liquid spray formation, by means X-ray technique requires the use of high energy sources.

The use of polycapillary half-lenses provides high flux beam – with a gain factor up to 10^3 than a pin-hole – and divergence values comparable with Synchrotron Radiation (~1mrad).

This allows conventional source for performing high resolution low contrast imaging and micro-Tomography to be used.

The results shown in this work are obtained through desktop experiments using an 8 keV Cu K? X-ray. Polycapillary semilens shapes the divergent X-ray beam into quasi-parallel and enables radiation focusing on the region of interest. High contrast focus images are collected by a CCD detector for X-radiation.

The inner structure of both biological samples and fast processes, like high pressure fuel injections, has been investigated through micro-Tomography technique. Quantitative measurements of mass concentration have been performed after a calibration process for liquid spray sample.

9207-34, Session 9

Phase imaging using polycapillary optics

Sajid Bashir, Jonathan C. Petruccelli, Carolyn MacDonald, Univ. at Albany (United States)

When X-rays pass through an object, the primary beam accumulates both attenuation and phase due to the object's material properties. Conventional X-ray image formation captures intensity, which measures attenuation. However, many materials are weakly attenuating and different materials of interest often present similar attenuation signatures. The ability to image phase in these cases would present a useful discriminant. However, phase imaging techniques require specialized sources that can generate a beam of a high degree of spatial coherence. For tabletop sources, the required degree of coherence generally requires small source features (10 to 50 micron). This is often achieved through the use of specialized microfocus sources or transmission masks placed in front of the source. In this work, the use of a polycapillary focusing optic (made of hollow glass tubes) is investigated in order to generate a focal spot of the necessary size from a conventional tabletop X-ray source. Optic and image characterization have been performed. Phase contrast images have been captured with two optics and pinholes of different sizes and preliminary results obtained for quantitative phase measurements.

9207-35, Session 9

Simulations and testing of high asymmetry angle x-ray crystal monochromators for advanced x-ray imaging applications

Zdenko Zápra?n?, Du?an Korytár, Peter ?iffalovi?, Matej Jergel, Edmund Dobro?ka, Slovak Academy of Sciences (Slovakia); Claudio Ferrari, Consiglio Nazionale delle Ricerche (Italy); Patrik Vagovi?, Ctr. for Free-Electron Laser Science (Germany); Petr Mikulík, Central European Institute of Technology (Czech Republic) and Masaryk Univ. (Czech Republic)

Advanced X-ray imaging techniques of weakly absorbing structures require an increase of the sensitivity to small refraction angles considering that they are based more on coherent X-ray phase contrast than on X-ray absorption one. Simulations of diffraction properties of germanium (Ge) X-ray crystal monochromators and of analyzer based imaging (ABI) method were performed for various asymmetry factors and several lattice plane orientations using an X-ray energy range from 8 keV to 20 keV. Using an appropriate phase/amplitude retrieval method one can recover the phase information from the ABI image, which is directly proportional to the projected electron density. We are using germanium based optics for X-ray imaging or image magnification. The use of Ge crystals offers several advantages over silicon (Si) crystals.

The integrated reflectivity of Ge crystals is two to three times larger than that of Si crystals. The spatial resolution of Ge magnifiers is typically two times better than the spatial resolution of Si magnifiers. We used high asymmetry diffractions to increase effectively the propagation distance and decrease the effective pixel size of the detector, to achieve a sufficient magnification of the sample and to improve coherence and increase output intensity. The most important parameter of a highly asymmetric monochromators as image magnifiers is the crystal surface quality. We have applied several crystal surface finishing methods including conventional mechanical lapping, chemical polishing, chemo-mechanical polishing and advanced nanomachining using single point diamond turning, and we have evaluated these methods by means of AFM, diffractometry, reciprocal space mapping and others.

9208-1, Session 1

Development of a two-stage x-ray focusing system with ultraprecise deformable mirrors

Takumi Goto, Satoshi Matsuyama, Hiroki Nakamori, Osaka Univ. (Japan); Takashi Kimura, Hokkaido Univ. (Japan); Yasuhisa Sano, Osaka Univ. (Japan); Yoshiki Kohmura, Kenji Tamasaku, Makina Yabashi, Tetsuya Ishikawa, RIKEN (Japan); Kazuto Yamauchi, Osaka Univ. (Japan)

We have developed an adaptive x-ray focusing optical system that consists of two-stage Kirkpatrick-Baez deformable mirrors. The optical system enables us to use focused x-rays with a controllable beam size at a fixed focal position under a diffraction-limited condition. To realize the optical system, we developed ultraprecise deformable mirror with a piezoelectric bimorph structure. It consists of a quartz glass substrate, 4 piezoelectric actuators and 18 electrodes. The substrate has dimensions of 50?100?t5 mm3. The four actuators, which have dimensions of 17.5?100?t1 mm3, were attached to the face and back sides of the substrate. To investigate the performance of the optical system, we performed a one-dimensional focusing test by using the two-stage optical system consisting of the two mirrors at BL29XUL of SPring-8 at an X-ray energy of 10 keV. To deform the mirrors to target elliptical shape, first, the mirrors were deformed by applying initial voltages predetermined with an off-line optical interferometer. Then, to finely correct deformation errors, we adjusted the applied voltages according to the mirror shape decided with the pencil-beam method. As a result, deformation accuracy of 6 nm (peak-to-valley) was achieved. In addition, a focused beam with full width at half maximum of 90 nm was obtained.

9208-2, Session 1

Beam transport and focusing layout based on adaptive optics for the SQS scientific instrument at the European XFEL

Tommaso Mazza, European XFEL GmbH (Germany); Riccardo Signorato, CINEL Strumenti Scientifici s.r.l. (Italy); Michael Meyer, Daniele La Civita, Maurizio Vannoni, Harald Sinn, European XFEL GmbH (Germany)

The SQS Instrument at the European XFEL is dedicated to the investigation of non-linear and ultra-fast processes in atoms, molecules and clusters using a variety of spectroscopic techniques in the soft X-rays wavelength regime. It will be equipped with a Kirkpatrick-Baez (KB) adaptive mirror system enabling a demagnification ratio as high as p/q = 300, a very large (~0.8m) clear aperture to minimize diffraction effects and the highest achievable surface quality (~50nrad RMS) in order to provide a sub-micron focusing for a broad range of photon energies (0.5 – 3 keV) and for different Beam Transport and focusing Layout (BTL) configurations. In this paper we describe the conceptual design of the BTL based on the KB system. The different BTL configurations will give the possibility of delivering both the full SASE and the monochromatic beam with variable focus sizes to three different interaction regions. This will be realized using adaptive optics equipped with prefigured elliptical substrates. The use of adaptive optics is selected here because (i) it gives the possibility to shape the mirrors to very aspherical profiles without affecting their surface quality and (ii) it allows shaping a sub-section of the substrate when the local bending requirement exceeds the capability of the actuators for the entire mirror surface. In this way the range of accessible BTLs can be extended. The paper includes the results of simulations determining the optimal geometrical parameters enabling the access to all the BTL configurations.

9208-4, Session 1

K-B bendable optics improvements at FERMI@Elettra FEL: last upgrade

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FERMI is the first seeded EUV-SXR free electron laser (FEL) user facility operated at Elettra Sincrotrone Trieste. Two of the three already operative beamlines, named LDM (Low Density Matter) and DiProI (Diffraction and Projection Imaging), make use of a Kirkpatrick-Baez (K-B) active X-ray optics system for focusing the FEL pulses in the beamlines. The present work reports on the results obtained from the optimization of the K-B optical system at the DiProI endstation. The aim of the optimization is to improve the system performances in terms of quality and size of the focal spot onto the sample controlling the fluence as well. To characterize the performances and develop reliable and reproducible focusing procedures we performed a campaign of measurements with several diagnostic systems, including a wavefront sensor mounted after the DiProI chamber. Online wavefront measurements have made possible the optimization of the bending acting on the mirror curvature and of the (pitch and roll) angle positions of the K-B system. From the wavefront measurements we have inferred a focal spot of 8 ?m x 6 ?m confirmed by the PMMA ablation imprints. The experimental results are compared with the predictions from simulations obtained using the WISE code, starting from the characterization of the actual mirror surface metrology. The results from simulations are in agreement with the experimental measurements. Filtering the Fourier transform of the mirror surface profiles, using the WISE code we have analyzed the impact of different spatial wavelengths on the focal spot degradation. For different energies of the incident beam we established the threshold where the focal spot degradation is no longer affected by the spatial wavelengths of the K-B mirror surfaces. Finally, we present the first test measurements of an improved prototype of the K-B bendable system with a different mechanical mounting (to better prevent the twisting effect), and with the addiction of piezo (to enhance the repeatability).

9208-5, Session 2

Toward large-area sub-arcsecond x-ray telescopes

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The future of x-ray astronomy depends upon development of x-ray telescopes with larger aperture areas (> 1 m^2) and finer angular resolution (< 1 arcsecond). Combined with the special requirements of nested grazing-incidence optics, the mass and envelope constraints of space-borne telescopes render such advances technologically challenging. Achieving this goal will require precision fabrication, alignment, mounting, and assembly of large areas (>100 m^2) of lightweight (≈ 1 kg m^-2 areal density) high-quality mirrors—possibly entailing active (in-space adjustable) alignment and figure correction. This paper discusses relevant programmatic and technological issues and summarizes progress toward large-area sub-arcsecond x-ray telescopes. Besides summarizing current research to develop active x-ray optics for astronomy, the paper reviews static approaches (mono-crystalline silicon, differential deposition, ion implantation, etc.) for precision figuring of lightweight mirrprs.

9208-6, Session 2

Technology requirements for a square-meter arcsecond-resolution telescope for x-rays: the SMART-X mission

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Addressing the astrophysical problems of the 2020's requires sub-arcsecond x-ray imaging with square meter effective area.

Such requirements can be derived, for example, by considering deep x-ray surveys to find the young black holes in the early universe (large redshifts) which will grow into the first supermassive black holes. We have envisioned a mission based on adjustable x-ray optics technology, in order to achieve the required reduction of mass to collecting area for the mirrors. We are pursuing technology which effects this adjustment via thin film piezoelectric "cells" deposited directly on the non-reflecting sides of thin, slumped glass.

While SMART-X will also incorporate state-of-the-art x-ray cameras, the remaining spacecraft systems have no more stringent requirements than those which are well understood and proven on the current Chandra X-ray Observatory.

9208-7, Session 2

Development status of adjustable grazing incidence x-ray optics using thin film PZT actuators

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Our proposed technology for the realization of sub-arcsecond, lightweight X-ray optics is based on the deposition of patterned thin film actuators, made of lead-zirconate-titanate (PZT), on the back of thermally-formed glass substrates. We are working on several technological challenges like the realization of substrates with sufficient initial quality, the achievement of sufficient control of shape corrections by means of piezoelectric actuators and the development of a stable and controllable alignment and integration process.

In this paper we report on our tangible progress and plans for achieving these goals.

9208-8, Session 2

Comparisons of the deflections of magnetically smart films on alloy of NiCo and glass substrates

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In developing techniques of new generation X-ray telescopes, the magnetically smart material (MSM) was applied to thin walled (~100-400 um thickness) electroformed alloy of NiCo or glass optics, and showed its advantages over the technique of electro-active actuators. It avoided embedding electrodes or wires in the manufacturing process to provide power to control the actuators and further to deform the mirrors. The deformation of MSM on substrates was achieved by applying non-contact external magnetic field. We made extensive measurements of the deflection versus magnetic field strength with White Light Interferometry in two different experimental configurations under applied magnetic field (0.04-0.16 T). One end of the sample was clamped in one configuration, and both ends of the sample were clamped in the other configuration. The 1.5 um thick MSM was deposited on the NiCo substrate of 60 um thick and 20 mm long, and the deflection on the order of 14 um was measured when the specimen was immersed in a magnetic field of 0.11 T with one end clamped. Different from the sample of NiCo substrate, the deflection of the sample of 100 um thick glass substrate was measured to be 3 um in a magnetic field of 0.11 T. When both ends of the sample were clamped, the deflections were smaller, and still large enough to correct mid-frequency (~2-10 mm length scales) ripple on mirrors. Furthermore, the deflections were successfully modeled by analytical method, and numerical analysis in COMSOL software.

9208-9, Session 3

Adjustable optics systems based on PZT thin films with integrated ZnO electronics

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Adjustable X-ray optics, using piezoelectric lead zirconate titanate (PZT) films deposited on slumped, thin glass substrates, are a candidate for the Square Meter Arc Second X-ray Telescope (SMART-X) mission concept. The vision is to create a pixelated array of 1 cm2 electrodes that are addressed using a row-column scheme, with ZnO transistors integrated onto the PZT to provide the control electronics. The ultimate mirror pieces will be shaped in the form of paraboloids and hyperboloids with an iridium reflective coating deposited on the concave surface of the glass and a PZT film deposited on the convex surface.

The PZT films were deposited on Corning Eagle glass substrates using RF magnetron sputtering. Results on the flat test pieces demonstrate that crystallization into the perovskite phase is complete at 550 C with piezoelectric properties that exceed the mission requirements. Influence function measurements of 2 ?m thick films show a 1.5 ?m out-of-plane deflection for 1 cm^2 actuators at a drive level of +1.5 Ec, in good agreement with finite element analysis models. Preliminary depositions on curved substrates mimicking the shape of the proposed mirror demonstrate the process can readily be transferred to non-planar geometries.

Highly accelerated lifetime tests suggest that, at low temperatures (<180°C), failure occurs by oxygen vacancy migration with an activation energy of 0.79 eV. The voltage acceleration was found to be 6. Estimates of the lifetime for a 1 Vc drive at 20 C using the Eyring equation imply the piezoelectric actuators should last well beyond the lifetime of the telescope. It is anticipated that the piezoelectric response may alter over time, requiring an adjustment of the applied volt-ages required to maintain the proper surface figure for the mirror. As a result, a strain gauge monitoring system, similar to those used in resistance bridges, is proposed for in-situ characterization of the mirror's shape.

For integration with the control electronics, ZnO thin film transistors are fabricated using plasma enhanced atomic layer deposition (PE-ALD), with Al_2O_3 layers to electrically isolate the ZnO from the underlying films. Incorporation of the ZnO processing shows no significant degradation to the PZT properties. The transistors exhibit rapid turn on times (~ ms). PZT capacitors were charged to 10 V and, in the transistor off state, exhibited discharge times consistent with negligible source-drain leakage. Integration of the ZnO transistors with the PZT arrays will be discussed.

9208-10, Session 3

Active shape correction of a thin glass/plastic x-ray mirror

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Optics for future X-ray telescopes will be characterized by very large aperture and focal length, and will be made of lightweight materials like glass or plastic in order to keep the total mass within acceptable limits. Optics based on thin slumped glass foils are currently in use in the NuSTAR telescope and are being developed at various institutes like INAF/OAB, aiming at improving the angular resolution to a few arcsec HEW. Another possibility would be the use of thin plastic foils, being developed at the Palermo University. Even if relevant progresses in the achieved angular resolution were recently made, a viable possibility to further improve the mirror figure would be the application of thin piezoelectric foils onto the non-optical side of the mirrors. In fact, thin foils are prone to deform, so they require a careful integration to avoid mirror deformations and even correct forming errors. This however offers the possibility to actively correct the residual deformation by modest forces exerted by a system of thin piezopolymers. Even if other groups are already at work on this idea, we are pursuing the concept of active integration of thin glass or plastic foils with piezoelectric stripes, fed by voltages driven by the feedback provided by X-rays in intrafocal setup at the XACT facility at INAF/OAPA. In this work, we show the preliminary results achieved with the very first prototypes realized in this project.

9208-11, Session 3

Test results for an AOA-Xinetics grazing incidence x-ray deformable mirror

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Space telescopes designed study the X-rays emitted by celestial bodies use grazing incidence mirrors to collect X-ray photons and form an image. These mirrors require extremely smooth surfaces with precise figures to provide well-focused beams and small image spot sizes. To achieve the collecting areas required to detect intrinsically faint sources, several thousand thin, doubly curved mirrors are arranged to form several hundred nested cylindrical shells to approximate a filled telescope aperture. For example, the Generation-X telescope that has been proposed by SAO as one of NASA's Astrophysics Strategic Mission Concepts would have a 12-meter aperture with a 50 m2 collecting area and 0.1 arc-second spatial resolution. This spatial resolution would be obtained by actively controlling the mirror figure with piezoelectric actuators deposited on the back or each 0.4 mm thick mirror segment. In 2009, as part of its support to the Generation-X study, Northrop Grumman used internal funds to look at the feasibility of using Xinetics proven deformable mirror technologies to meet the Generation-X mirror requirements.

In 2010 we designed, fabricated two 10 x 30 cm Platinum-coated silicon mirrors with 108 surface-parallel electrostrictive Lead Magnesium Niobate (PMN) actuators bonded to the mirror substrates. PMN actuators are highly reliable; exhibit little to no hysteresis, aging or creep; and can be closely spaced to correct low and mid-spatial frequency errors in a compact package. These mirrors were tested at optical wavelengths by Xinetics to assess the actuator's performance, but no funds were available for X-ray tests.

In 2013 after receiving an invitation to evaluate the mirror's performance at Argonne National Laboratory they were taken out of storage, refurbished, retested at Xinetics and transported to ANL for metrology measurements with a Long Trace Profilometer and a Fizeau laser interferometer, and X-ray testing with an 18 Kev beam.

In this paper we discuss the development and testing of these adaptive x-ray optics at AOA-Xinetics. Marathe, et al, will present the results of the tests at Argonne at this conference.

9208-12, Session 3

Development of single grating x-ray Talbot interferometer as a feedback loop sensor element of an adaptive x-ray mirror system

Shashidhara Marathe, Xianbo Shi, Naresh G. Kujala, Michael J. Wojcik, Ali M. Khounsary, Jun Qian, Albert Macrander, Lahsen Assoufid, Argonne National Lab. (United States)

Recently, there has been an increased interest in using adaptive optics technology for X-ray optics applications [1-2]. One of the key elements of an adaptive optics system is the real time wavefront sensor for the feedback in a closed loop system. The X-ray grating Talbot interferometer (XGTI) has been shown to be a very useful tool for high accuracy at-wavelength wavefront sensing [3]. The technique has many advantages including simple setup, fast data acquisition, and being robust against mechanical vibrations. More recently, S. Matsuyama et al [4] have performed the measurement of wavefront from a hard-X-ray nanobeam using a one dimensional single-grating interferometry based on the Talbot effect and the Fourier transform method.

In this paper, we report on the implementation of 2D single grating x-ray Talbot interferometer as a feed-back loop sensor element of an adaptive x-ray mirror system. The initial test of this concept was performed at the Advanced Photon Source, 1-BM-B beamline in collaboration with Northrop-Grumman using a deformable Pt coated on Silicon mirror. The mirror has 108 individually controlled actuators laid in four rows of 27 actuators each that allow it to be deformed into a variety of shapes such as flat, cylindrical, and ellipsoidal. The mirror was tested in five different actuation configurations and the reflected interferograms were measured using 18 keV x-ray and a single 2D, $\pi/2$ phase grating. With each actuation configuration, the wavefront at the location of the interferometer was retrieved and back propagated in free space to the position of the mirror, where the surface height profile of the mirror was reconstructed. These in-situ measurement results were also compared with the ex-situ metrology data obtained using the Long Trace Profilometer and the Fizeau laser interferometer.

[1] Tyson, Principles of Adaptive Optics, third edition, 14, (2010).

[2] A. Khounsary, S. O'Dell, and T. Beano, Adaptive X-ray Optics II, SPIE Proc. Vol. 8503, 2012.

[3] Simon Rutishauser, Liubov Samoylova, Jacek Krzywinski et al., Nature communications, 3:947 DOI: 10.1038 (2012).

[4] Satoshi Matsuyama, Hikaru Yokoyama, Ryosuke Fukui, Yoshiki Kohmura, et al, Vol. 20, Opt. Express 24977-86, (2012).

9208-13, Session 3

Design and fabrication of a high precision x-ray deformable mirror

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AOA-Xinetics has been developing been developing techniques for shaping grazing incidence optics with surface-normal and surface-parallel electrostrictive Lead magnesium niobate (PMN) actuators bonded to mirror substrates for several years. These actuators are highly reliable; exhibit little to no hysteresis, aging or creep; and can be closely spaced to correct low and mid-spatial frequency errors in a compact package. In this paper we discuss the design of a 45cm grazing incidence mirror fitted with 45 PMN actuators and integral strain gauges and temperature sensors that allow sub-nanometer control of the surface figure. This will permit the surface errors due to optical fabrication to be corrected and will allow near ideal x-ray imaging performance to be achieved. Results from the optical testing of the first prototype mirror will be presented. The mirror is now at Lawrence Livermore Nat'l. Labs and a related paper will present the results of the initial testing performed there.

9208-14, Session 3

Control of a 45-cm long x-ray deformable mirror with either external or internal metrology

Lisa A. Poyneer, Thomas J. McCarville, Tommaso Pardini, David W. Palmer, Lawrence Livermore National Lab. (United States); Audrey D. Brooks, Northrop Grumman Xinetics (United States)

We present our most recent results in controlling a 45-cm long x-ray deformable mirror. Its surface figure is measured with high-precision visible-light interferometry. Using this metrology and custom control algorithms, we have actuated the x-ray deformable mirror and flattened its entire surface to as good as 0.7 nm rms controllable figure error. The mirror's figure, as well as the overall sphere, changes with time due to small temperature changes in the laboratory and non-linear effects in the PMN actuators. We plan to use feedback from the mirror's internal temperature sensors and strain gauges to maintain its figure and sphere, independent of external metrology. LLNL-ABS-649074.

9208-19, Session 3

Using ion implant to change the figure of extremely thin and lightweight optics

Larry A. Hess, Kai-Wing Chan, Ryan S. McClelland, William W. Zhang, NASA Goddard Space Flight Ctr. (United States)

Lightweight and thin optics will be essential components of future x-ray astronomical missions. These optics, thin and flexible, are easily distorted by inadvertent stresses, including surface effects arising during their fabrication and coating. To devise an approach to mitigate the effects of these stress, we have recently started an effort to use ion implant to change two key parameters of an x-ray mirror segment: cone angle and sag. In this paper we report on our initial work of changing the curvatures of single crystal silicon wafers, measuring the effects of ion implant and comparing them with finite element analysis. This is the first of a two phases of our effort. In the second phase, we will apply the quantitative knowledge learned from flat wafers to nearly cylindrical x-ray mirror segments, improving their cone angles and axial sags to achieve higher quality x-ray images.

9208-15, Session 4

Structure in defocused beams of x-ray mirrors: causes and possible solutions

John P. Sutter, Simon G. Alcock, Diamond Light Source Ltd. (United Kingdom); Fiona Rust, Univ. of Bath (United Kingdom); Hongchang Wang, Diamond Light Source Ltd (United Kingdom); Kawal Sawhney, Diamond Light Source Ltd. (United Kingdom)

Grazing incidence mirrors are now a standard optic for focusing X-ray beams. Both bimorph and mechanically bendable mirrors are widely used at Diamond Light Source because they permit a wide choice of focal lengths. They can also be deliberately set out of focus to enlarge the X-ray beam, and indeed many beamline teams now wish to generate uniform beam spots of variable size. However, progress has been slowed by the appearance of fine structure in these defocused beams. Measurements showing the relationship between the medium-frequency polishing error and this structure over a variety of beam sizes will be presented. A theoretical model for the simulation of defocused beams from general mirrors will then be developed. Not only the figure error and its first derivative the slope error, but also the second derivative, the curvature error, must be considered. In conclusion, possible ways to reduce the defocused beam structure by varying the actuators' configuration and settings will be discussed.

9208-16, Session 4

Analysis of active figure control effects on mounting strategy for x-ray optics

Jeffery J. Kolodziejczak, Jacqueline M. Roche, Stephen L. O'Dell, Brian D. Ramsey, Ronald F. Elsner, Mikhail V. Gubarev, Martin C. Weisskopf, NASA Marshall Space Flight Ctr. (United States)

As part of ongoing development efforts at MSFC, we have begun to investigate mounting strategies for highly nested x-ray optics in both full-shell and segmented configurations. The analytical infrastructure for this effort also lends itself to investigation of active strategies. We expect that a consequence of active figure control on relatively thin substrates is that errors are propagated to the edges, where they might affect the effective precision of the mounting points. Based upon modeling, we describe parametrically, the conditions under which active mounts are preferred over fixed ones, and the effect of active figure corrections on the required number, locations, and kinematic characteristics of mounting points.

9208-17, Session 4

An error function minimization approach for the inverse problem of adaptive mirrors tuning

Maurizio Vannoni, Fan Yang, European XFEL GmbH (Germany); Frank Siewert, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Harald Sinn, European XFEL GmbH (Germany)

Adaptive x-ray optics are more and more used in synchrotron beamlines, and it is probable that they will be the most common choice even for the next high-power free-electron laser sources, as the European XFEL now under construction in Hamburg, or similar projects currently ongoing. These facilities will deliver a high power beam, with an expected high heat load on the optics, and bendable mirrors are required to actively compensate the resulting wavefront distortion. On top of that, the mirror could have also intrinsic surface defects, as polishing errors or mounting stresses. In order to be able to correct the mirror surface with a high precision and inside the designed range, the mirror is usually characterized with a high accuracy metrology to calculate the actuators pulse functions and to assess its initial shape. After that, singular value decomposition (SVD) is used to find the signals to be applied into the actuators, to reach the desired surface deformation or correction. But in some cases this approach could be not robust enough for the needed performance. We present here a comparison between the classical SVD method and an error function minimization based on root-mean-square calculation. Some examples are provided, using a simulation of the European XFEL mirrors design, and the expected performances are evaluated in order to reach the ultimate quality in different scenarios. The approach could be easily generalized to other cases as well.

9208-18, Session 4

Microfocusing beamline for XUV-XUV pump-probe experiments using HH generation

Fabio Frassetto, Istituto di Fotonica e Nanotecnologie (Italy); Sunilkumar Anumula, Francesca Calegari, Andrea Trabattoni, Mauro Nisoli, Politecnico di Milano (Italy) and Istituto di Fotonica e Nanotecnologie (Italy); Luca Poletto, Istituto di Fotonica e Nanotecnologie (Italy)

The possibility of obtain 10 um order focal spot in the xuv region opens the way to xuv-xuv experiments in HHG beamlines. Here are presented the first results (throughput and focal quality) of a beamline designed for this purpose. The peculiarity of the optical design relies on the use of only toroidal mirrors in place of more expensive Cartesian optics. The coma aberration, usually dominating the quality of the focal spot when toroidal mirrors are used with high levels of de-magnification, is compensated using two mirrors in a subtractive configuration. A third toroidal mirror decouples the length of the exit arm from the magnification factor, in this way the exit arm can be chosen to install even a rather large experimental chamber. Three mirrors with optical power are required, in order to assure an optimal focalization. In order to guarantee a day-to-day reproducible working condition, the mirrors are mounted on remotely adjustable optical stages, that are controlled via a genetic algorithm with the feedback on the quality of the focal spot. This solution helps the users to reach the best focalization conditions in a very short time, of the order of few minutes. The beam splitting for the xuv-xuv pump-probe is obtained using two flat mirrors in grazing incidence, each of one reflecting half of the beam. The results obtained during the commissioning phase are presented. Emphasis is placed in the characterization of the spot size and in the characterization of the performances of the genetic algorithm.

9209-31, Session PMon

Separation of Hard X-Ray Synchrotron Radiation from Electron Beam Slices

An He, Oleg Chubar, Lihua Yu, Brookhaven National Lab. (United States)

In the new electron beam slicing scheme considered for National Synchrotron Light Source II, a high charge (200pC) bunch (slicing bunch) with very short bunch length (~148fs) and very small beam size (?x~46?m, ?y~25?m) from a low energy linac can be used to generate a slice of electron bunch from the storage ring bunch (core bunch). The thin slice bunch and the "core" bunch pass through the 3m long U20 in-vacuum undulator and radiate X-ray pulses of 170 fs and 30 ps length respectively. In this paper we propose a conceptual optical scheme allowing for the separation of the satellite radiation from the "core" (profiting from the spatial and angular differences in the vertical phase space of the two bunches) and the transport the short x-ray pulse to a sample. The scheme includes a pre-focusing compound refractive lens or a mirror, a secondary source aperture and a final focusing mirror. To get reliable estimates of the separation performances, a wavefront propagation study was performed using the "Synchrotron Radiation Workshop" (SRW) physical optics computer code.. As calculations show, at 7.8 keV, the separation signal-to-noise ratio can reach 5~10 and the satellite photon flux per pulse at sample can be ~5000-10000 photons/sec/0.1%BW depending on the separation method and the crossing angle between the slicing and the core bunches. Since the repetition rate can reach 100 kHz, the average flux per second can reach 5e8~1e9 photons/sec/0.1%BW.

9209-32, Session PMon

WaveProperGator: interactive framework for x-ray FEL optics design and simulation

Alexey Buzmakov, A.V. Shubnikov Institute of Crystallography (Russian Federation); Oleg Chubar, Brookhaven National Lab. (United States); Liubov Samoylova, Harald Sinn, European XFEL GmbH (Germany)

The simulations based on wave optics have become indispensable for beamline design for highly coherent novel X-ray sources such as X-ray Free Electron Lasers (XFEL). We present a new interactive framework package for coherent and partially coherent X-ray wavefront propagation simulations – "WaveProperGator" (WPG). The package has been developed at European XFEL to facilitate for the end users (beamline scientists and XFEL users) the designing, optimizing and improving X-ray optics to meet their experimental requirements. Our package uses SRW C/C++ library and its Python binding for wavefront propagation simulations. The tool allows for changing source and optics parameters and visualizing the results interactively. The framework is cross-platform: it runs reliably on Linux, MS Windows 7, and Mac OS X. Using IPython as a web-frontend make the users possible run the code at a remote server as well as at their local personal computer. One can use popular Python libraries (such as scipy, numpy, matplotlib) for pre- and post-processing as well as for visualization of the simulation results. The wavefronts are saved in HDF5 format for the eventual further processing and start-to-end simulations of experiments. The HDF5 format allows for keeping the calculation history within a single file, thus facilitating communication between various scientific groups, as well as cross-checking with other simulation results. The WPG source code together with guidelines for installation and application examples are available on the web. Several application examples, specific for XFEL, will be presented.

9209-33, Session PMon

A proposal for an open source graphical environment for simulating x-ray optics

Luca Rebuffi, Sincrotrone Trieste S.C.p.A. (Italy); Janez Demsar, Univ. of Ljubljana (Slovenia); Niccolo Canestrari, Oleg Chubar, Brookhaven National Lab. (United States); Manuel Sanchez del Rio, ESRF - The European Synchrotron (France)

Computer simulation of optical instruments is a mandatory step in the project, design and optimization of a synchrotron beamline. Most software used for X-ray optics simulation is developed in academic and research institutions and some of them are Open Source projects. Two examples are the SHADOW[1] and SRW[2] codes. Although these two codes have the same goal, the simulation of an X-ray beamline, they are complementary because the physical models used are different: geometrical optics (ray tracing) for SHADOW and physical optics (wave propagation) for SRW. A potential user would like to use both of them in the most compatible mode (using the same environment and ideally the same interface), and exchange input data and results between them. With this philosophy in mind, we will develop a graphic environment that commonly drive these and other codes that aim to create a virtual experiment, starting from the description of the electron beam, the emitted radiation, the optics and finally the sample scattering and detection.

We present ideas, specifications and solutions envisaged for creating an Open Source environment for X-ray optics simulations. Python is chosen as common interaction language, because both SHADOW and SRW already have a Python API. We describe the ingredients of the new application, a glossary of variables for optical component, the selection of visualization tools, and the integration of all these components in a high level workflow environment built on ORANGE [3]. Some prototypes are presented, and an invitation to collaborate in this project is launched.

[1] M. Sanchez del Rio, N. Canestrari, F. Jiang and F. Cerrina, "SHADOW3: a new version of the synchrotron X-ray optics modelling package" J. Synchrotron Rad. (2011). 18, 708-716 http://dx.doi.org/10.1107/S0909049511026306

[2] O. Chubar, P. Elleaume, "Accurate And Efficient Computation Of Synchrotron Radiation In The Near Field Region", proc. of the EPAC98 Conference, 22-26 June 1998, p.1177-1179. https://github.com/ochubar/SRW

[3] http://orange.biolab.si/

9209-34, Session PMon

Simulation of the ultrahigh energy resolution IXS analyzer system at NSLS-II

Alexey Y. Suvorov, David S. Coburn, Alessandro Cunsolo, Jeffrey W. Keister, Yong Q. Cai, Brookhaven National Lab. (United States)

The ultrahigh energy resolution IXS spectrometer being developed at the National Synchrotron Light Source II (NSLS-II) employs an innovative optical design. Its analyzer system utilizes an L-shaped laterally graded multilayer mirror in tandem with a multi-crystal arrangement. The multi-crystal arrangement explores the angular dispersion effect in extremely asymmetric Bragg reflections to achieve sub-meV energy resolution at an energy of about 9.1 keV. Its angular acceptance (~ 0.1 mrad) is about two orders of magnitude lower than the spherically-bent backscattering analyzers conventionally used in other IXS spectrometers. The L-shaped laterally graded multiplayer mirror was designed to increase the angular acceptance of this new multi-crystal optics to a comparable level.
It performs angular collimation of the incoming beam from about 15 mrad down to 0.1 mrad in both vertical and horizontal directions. Here

we present simulations of the mirror performance and positioning and stability requirements in conjunction with the multi-crystal energy analyzer.

9209-35, Session PMon

An open software framework for advancement of x-ray optics simulation and modeling

David L. Bruhwiler, RadiaSoft LLC (United States); Oleg Tchoubar, Brookhaven National Lab. (United States); Jacek Krzywinski, Amber Boehnlein, SLAC National Accelerator Lab. (United States)

Accurate physical-optics based simulation of emission, transport and use in experiments of fully- and partially-coherent x-ray radiation is essential for both designers and users of experiments at state-of-the-art light sources – low-emittance storage rings, energy-recovery linacs and free-electron lasers. To be useful for different applications, the simulations must include accurate physical models for the processes of emission, for the structures of x-ray optical elements, interaction of the radiation with samples, and propagation of scattered x-rays to a detector. Based on the “Synchrotron Radiation Workshop” (SRW) open source computer code, we are developing a simulation framework, including a graphical user interface, web interface for client-server simulations, data format for wave-optics based representation of partially-coherent x-ray radiation, and a dictionary for universal description of optical elements. Also, we are evaluating formats for sample and experimental data representation for different types of experiments and processing. The simulation framework will facilitate start-to-end simulations by different computer codes complementary to the SRW, e.g. GENESIS and FAST codes for simulating self-amplified spontaneous emission, SHADOW and McX-Trace geometrical ray-tracing codes, as well as codes for simulation of interaction of radiation with matter and data processing in experiments exploiting coherence of radiation. The development of the new framework is building on components developed for the Python-based RadTrack software, which is designed for loose coupling of multiple electron and radiation codes to enable sophisticated workflows. We are exploring opportunities for collaboration with teams pursuing similar developments at ESRF and the European XFEL.

9209-36, Session PMon

Aberration free short focal x-ray lenses

Lucia Alianelli, Diamond Light Source Ltd. (United Kingdom); Manuel Sanchez del Rio, ESRF - The European Synchrotron (France)

Refractive and refractive-diffractive optics, used to focus or collimate beams of hard x-rays, find applications in several x-ray techniques including diffraction, imaging, small angle scattering. Nowadays refractive lenses are used in very large energy range, even to focus x-ray with energy E > 100 keV, and, in a large range of focal lengths, from tens of meters down to few millimeters.

We treat the problem of defining the ideal x-ray refractive lens design for point focusing of x-ray beams from third generation synchrotron sources. This design applies to ultra-short focal length lenses, with very highly curved surfaces. The task is accomplished by use of the Fermat’s principle to define a lens shape that is completely free from geometrical aberrations. Current micro-fabrication resolution limits are identified and a lens design is chosen which will tolerate the fabrication errors. Finally the chromatic aberrations are calculated for some typical x-ray perfect crystal monochromators. It is shown that a refractive lens delivering single-digit nanometer sized focused x-ray beam is within reach of current design and micro-fabrication techniques.

X-ray optics simulations illustrating the lack of aberrations in the proposed ultra-short focal optics are presented.

9209-37, Session PMon

A new SHADOW update: integrating diffraction effects into ray tracing

Xianbo Shi, Argonne National Lab. (United States); Manuel Sanchez del Rio, ESRF - The European Synchrotron (France); Ruben Reininger, Argonne National Lab. (United States)

We describe the new implementation in the ray tracing code SHADOW based on a “hybrid method” developed recently [1]. The code calculates the diffraction effects from an optical element by means of wavefront propagation, and combines the result with that from regular ray tracing. This hybrid procedure is automatically invoked when diffraction is present (e.g., beam clipped by an aperture or the finite size of the optics), or by user demand. The code also enables the simulation of mirror figure errors in the selected manner, i.e., as geometrical optics or as wave optics. Finally, the applicable conditions and limitations of the new code are discussed in detail.

[1] Shi, X., Reininger, R., Sanchez del Rio, M., and Assoufid, L., “A hybrid method for X-ray optics simulation: combining geometric ray tracing and wavefront propagation,” J. Synchrotron Rad. (2014) Submitted.

9209-38, Session PMon

An efficient wave-optics simulation method for beamlines containing extended focusing mirrors

Niccolo Canestrari, Oleg Chubar, Brookhaven National Lab. (United States)

A new method to model grazing incidence reflective optical elements of different geometrical shapes has been implemented in the “Synchrotron Radiation Workshop” (SRW) computer code. It is based upon a local stationary phase expansion, which is similar to the propagation of the electric field along geometrical rays within the optical element. This method is CPU-efficient and fully compatible with the numerical methods of the Fourier optics. The new method has been benchmarked against the geometrical ray-tracing code SHADOW. The test simulations have been performed for cases without and with diffraction at mirror apertures, including cases where the grazing-incidence mirrors can be hardly approximated by ideal thin lenses. Good agreement between the SRW and SHADOW simulation results is observed in the cases without diffraction. The differences between the simulation results obtained by the two codes in diffraction-dominated cases for illumination with fully- or partially-coherent radiation are analyzed and interpreted. The CPU performance of the new wavefront propagation method for the grazing incidence mirror is comparable to the standard “thin” lens propagation method, with only a modest increase of the execution time, which allows for its efficient use in simulation of complicated X-rays optics beamlines in modern light source facilities.

9209-39, Session PMon

Fourier transform image processing techniques for grid-based phase imaging

Sajjad Tahir, Carolyn MacDonald, Jonathan C. Petruccelli, Univ. at Albany (United States)

A recently developed technique for phase imaging using tabletop sources is to use multiple fine-pitch gratings. However, the strict manufacturing tolerances and precise grating alignment required have limited the widespread adoption of grating-based techniques. An alternative, technique, based on a single grid of much coarser pitch was recently demonstrated by Bennett et al, [Med. Phys. 37 (11) November 2010]. Here we investigate the use of a mammography grid for this technique. Images were obtained with low power (50 W) Rh source and focused mammography grids of 200-300 µm periods. A camera with 22 µm pixels was used to provide sufficient spatial resolution to resolve the dark fringes. Phase images were obtained from the raw images by isolating the region surrounding the spatial harmonics of the grid in the Fourier domain. The first order harmonic spectrum was separated from the zeroth order and then inverted to produce the zeroth order absorption image and first order harmonic image. The zeroth order harmonic image has only been attenuated by absorption and large angle Compton scattering while the higher order harmonic images contain absorption as well as small angle refraction and diffraction, so that the ratio yields pure phase information. The effects on the final images of varying grid, object, and detector distances, and of a variety of windowing functions, used to separate the harmonics, were investigated. The signal peak heights and blur produced in the DPC image were analyzed by varying the width of the Gaussian window.

9209-1, Session 1

Generation and transport of high-coherence x-rays: current status and future prospects *(Invited Paper)*

Kwang-Je Kim, Argonne National Lab. (United States)

The x-ray coherence from undulators will increase significantly as the storage ring technology advances from the third generation to the future multi-bend achromat configurations. X-ray free electron lasers (XFELs), two of which are currently operating and more under construction, produce self-amplified spontaneous emission (SASE) with full transverse coherence and femtosecond time resolution but with chaotic temporal spectra. However, it is possible to improve the temporal coherence of SASE by self-seeding and other schemes. An x-ray free-electron laser oscillator (XFELO) can provide full spatial and temporal coherence with high spectral purity and stability. For advanced x-ray utilization, optimization of the x-ray beamline configuration, involving apertures, curved mirrors, etc, is as important as the production of high-coherence x-rays. The issues in beamline modeling include effect of mirror roughness, aberration from the grazing incidence geometry, change of the polarization state, etc. Much progress has been made during the last several decades in understanding the physics and in developing modelling of generation and transport of the x-ray beams. In the future, the demand on the precision and efficiency of the modelling will become more challenging to keep up with the anticipated stringent user specifications for next generation of applications. After an overview of the current status, we will attempt to project the future development in the x-ray production and transport.

9209-2, Session 1

Partial coherence and imperfect optics at a synchrotron radiation source modeled by wavefront propagation *(Invited Paper)*

David Laundy, Simon G. Alcock, Lucia Alianelli, John P. Sutter, Kawal Sawhney, Diamond Light Source Ltd. (United Kingdom); Oleg Chubar, Brookhaven National Lab. (United States)

Hard X-ray undulator radiation at 3rd generation storage rings falls between the geometrical and the fully coherent limit and cannot be completely modeled by incoherent ray tracing or by fully coherent wave propagation. In addition, X-ray optics such as mirrors introduce unavoidable distortions on the wavefront. We have used the the wavefront propagation code Synchrotron Radiation Workshop (SRW) running in a Python environment to model partial coherence. We have also modeled distortion of the wavefront using measured surface errors on the mirrors.

9209-3, Session 1

Simulations applied to focusing optics at European XFEL *(Invited Paper)*

Liubov Samoylova, Harald Sinn, European XFEL GmbH (Germany)

European X-ray Free Electron Laser (XFEL) in Hamburg will deliver the X-ray femtosecond pulses with up to 10^12 photons per pulse, with high repetition rate up to 4.5 MHz and will be most powerful in comparison with existing facilities, LCLS in Stanford and SACLA in Japan. For beam conditioning all the end stations at European XFEL will rely on focusing optics, the grazing incidence KB mirrors or CRLs at some hard X-ray beamlines. There are many factors that make the requirements on X-ray optics very challenging: full transverse coherence, large distances and, as a consequence, large apertures on the optics; wide photon energy ranges, 3-25 keV from hard X-rays undulator beamlines SASE1, SASE2, and 0.25-3.5 keV from soft X-rays undulator beamline SASE3, and, correspondingly, varying beam size and divergence. Last but not least, most of optical elements will be located underground in tunnel, that imposes additional requirements on optics robustness. For proper design and optics specifications, one faces the design problems that require the full-scale wavefront simulations, with taking into account optics imperfectness and diffraction effects on apertures. The application examples of wavefront simulations for various focusing optics schemes at European XFEL, such as extreme focusing with long KB mirrors, concurrent impact of diffraction on the apertures of the mirrors cutting the beam and quality of the mirror surfaces, and CRLs collimation and focusing of the XFEL beam will be presented. The status of framework for start to end simulation for single particle imaging experiments will be also discussed.

9209-4, Session 1

Simulations of x-ray optics for ESRF-Upgrade programme

Manuel Sanchez del Rio, ESRF - The European Synchrotron (France)

The ESRF Upgrade includes construction of long beamlines to use routinely nano-beams. This requires a very high demagnification of the ESRF source, which makes beamline optics design a fundamental concept for the future availability of bright and small stable beam. Some examples of recent ray-tracing simulations for Upgrade beamlines are be presented, including transfocators, bent crystals and graded multilayers. In parallel, an ambitious project for the upgrade and integration of existing software and development of new toolbox will be discussed, with particular interest in beam polarization and partial coherence.

9209-5, Session 2

Developments toward a framework for simulation at state-of-the-art x-ray facilities *(Invited Paper)*

Garth J. Williams, SLAC National Accelerator Lab. (United States)

As experimental concept and execution becomes increasingly complex across the spectrum of user-driven light sources, data analysis becomes more complicated and the urgency of completing an experiment on the first attempt grows. It has become apparent that simulation of the expected signal from such experiments can increase the likelihood of success of a particular experiment and the efficiency of a facility as a whole. Here, we propose a modular approach to the simulation problem, which will build on existing expertise and software. Additionally, we are working to support the simulation of partially coherent fields where the photon degeneracy parameter is much larger than unity.

9209-6, Session 2

Recent updates in the Synchrotron Radiation Workshop code: on-going simulation activities for storage rings and x-ray FEL and plans for the future

Oleg Chubar, Brookhaven National Lab. (United States)

The "Synchrotron Radiation Workshop" wave optics computer code that was started in 1997 in the Accelerator Division of the European Synchrotron Radiation Facility (ESRF) has experienced several important updates over the last few years. The updates and changes were made in the organization of developments, key functionalities, scope and applications of the code. The main organizational change was the transition of the code to the Open Source development standard, according to the preceding agreement between ESRF, Brookhaven National Laboratory (BNL), US Department of Energy and other contributed institutions. This transition greatly facilitated further development of the code (for x-ray optics and in other areas) as well as its use, either directly or within other software packages, by scientists and engineers from different laboratories. Among new functionalities recently implemented in the code one can mention physical optics based "propagators" for grazing-incidence mirrors (thanks to collaboration between BNL and ESRF) and for perfect crystals (thanks to collaboration between BNL and DIAMOND Light Source). Detailed wave-optics simulations are now routinely performed using the SRW under Python for beamlines of the National Synchrotron Light Source II at BNL, for the European XFEL, and for other light sources. Special efforts are planned to be dedicated in the nearest future to establishing of a convenient "framework" for inter-operation with other codes with complementary functions.

9209-7, Session 3

Propagation of coherent light pulses with PHASE *(Invited Paper)*

Johannes Bahrdt, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Uwe Flechsig, Paul Scherrer Institut (Switzerland); Walan Grizzoli, Max IV Project (Sweden); Frank Siewert, Helmholtz-Zentrum Berlin (Germany)

The current status of the software package PHASE for the propagation of coherent light pulses along a synchrotron radiation beamline is presented. PHASE is based on an asymptotic expansion of the Fresnel-Kirchhoff integral which is usually terminated at the 2nd order (stationary phase approximation). The limits of this approximation as well as possible extensions to higher orders are discussed. The accuracy is benchmarked against a direct integration of the Fresnel-Kirchhoff integral. PHASE can be run either from a built-in graphical user interface or from any script language which provides substantial flexibility. Short range slope errors or apertures can easily be realized. Examples will be given. Complete wave packages can be propagated, as well. Fourier propagators are included in the package, thus, the user may chose between a variety of propagators. Several means to speed up the computation time were tested - among them are the parallelization in a multi core environment and the parallelization on a cluster.

9209-8, Session 3

X-ray optics simulation and beamline design using a hybrid method *(Invited Paper)*

Xianbo Shi, Ruben Reininger, Argonne National Lab. (United States); Manuel Sanchez del Rio, ESRF - The European Synchrotron (France); Jun Qian, Lahsen Assoufid, Argonne National Lab. (United States)

A hybrid method combining ray tracing and wavefront propagation was recently developed for X-ray optics simulation and beamline design and optimization [1]. The benchmarking of the hybrid method and its implementation into the SHADOW ray tracing package are described elsewhere [1, 2]. One major application of the hybrid method is to investigate the effects of figure errors on the performance of focusing mirrors. As synchrotron facilities with low emittance and high brilliance are built or planned, significant efforts have been made to produce ultra-smooth mirrors for providing diffraction-limited focus as well as for preserving the coherence of the X-ray beam. A previous study [1] suggested that wave optics is more appropriate than ray tracing in simulating the effect of figure errors of ultra-smooth mirrors. In the present work, the beam intensity profiles in the vicinity of the focal plane of an elliptical cylinder mirror with different figure errors are simulated using three available wave optics methods: the hybrid code based on the Fourier optics approach [1], the Stationary Phase method [3-5] and the technique based on the direct Fresnel-Kirchhoff diffraction integral [6, 7]. The advantages and limitations of each wave optics method is discussed. We also present simulations performed with the hybrid method using the figure errors of an elliptical cylinder mirror coated and measured at APS [6] using microstitching interferometry. These results show that the hybrid method provides accurate and quick evaluation of the expected mirror performance making it a useful tool for designing diffraction-limited focusing beamlines.

[1] Shi, X., Reininger, R., Sanchez del Rio, M., and Assoufid, L., "A hybrid method for X-ray optics simulation: combining geometric ray tracing and wavefront propagation," J. Synchrotron Rad. submitted (2014).

[2] Shi, X., Sanchez del Rio, M., and Reininger, R., "A new SHADOW update: integrating diffraction effects into ray tracing," These proceedings.

[3] Bahrdt, J., "OpticsWave front propagation in synchrotron radiation beamlines," Appl. Opt. 36, 4367–4381 (1997).

[4] Bahrdt, J., Flechsig, U., Gerhardt, S. and Schneider, I., "PHASE, a Universal Software Package for the Propagation of Time- Dependent Coherent Light Pulses along Grazing Incidence," Proc. SPIE 8141, 81410E (2011).

[5] Reininger, R., Feldhaus, J., Gürtler, P. and Bahrdt, J., "Wavefront propagation through the beamline designed for seeding the DESY XUV FEL," Nucl. Instrum. Methods Phys. Res. A 467, 38–41 (2001).

[6] Kewish, C. M., Assoufid, L., Macrander, A. T. and Qian, J., "Wave-optical simulation of hard-x-ray nanofocusing by precisely figured elliptical mirrors," Appl. Opt. 46, 2010–2021 (2007).

[7] Kewish, C. M., Macrander, A. T., Assoufid, L. and Qian, J., "Comparison of two methods for simulation of hard X-ray nanofocusing by elliptical mirrors," Nucl. Instrum. Methods Phys. Res. A 582, 138–141 (2007).

9209-9, Session 4

A powerful scriptable ray tracing package xrt *(Invited Paper)*

Konstantin Klementiev, MAX IV Lab. (Sweden); Roman Chernikov, Deutsches Elektronen-Synchrotron (Germany)

We present an open source python based ray tracing tool that offers several unique features. It started with the goal of combining more visual information in ray-traced images than other ray tracing codes typically offer. By using colors and brightness, xrt can simultaneously encode energy, or other beam characteristics, and flux. In the course of the development, also other aspects of ray tracing ? material properties, combination with diffractive and refractive elements, preservation of polarization properties, implementation of complex (also closed) surfaces, multiprocessing and portability ? have been thoroughly addressed. The package has many usage examples which are supplied together with the code and visualized on its web page.

We exemplify the present version (0.9.1 as of February 2014, available at pythonhosted.org/xrt) by modeling (i) a curved crystal analyzer, (ii) a quarter wave plate, (iii) Bragg-Fresnel optics and (iv) multiple reflective and non-sequential optics (polycapillary).

The development version has success in implementation of OpenCL framework that executes calculations on both CPUs and GPUs. Currently, the calculations of an undulator source on a GPU show a gain of more than two orders of magnitude in computing time. The development version is also successful in calculating the Kirchhoff integral that is used for the reconstruction of wave fronts. The latter enables us, for example, to calculate grating efficiencies. We present the latest development results as well.

9209-10, Session 4

Novel applications of the x-ray tracing software package McXtrace *(Invited Paper)*

Erik B. Knudsen, Martin M. Nielsen, Kristoffer Haldrup, Technical Univ. of Denmark (Denmark); Eric J Topel, St. Olaf College (United States); Søren Schmidt, Technical Univ. of Denmark (Denmark)

We will present several examples of applying the X-ray tracing software package McXtrace to different kinds of X-ray scattering experiments. In particular we will focus on time-resolved type experiments. Simulations of full scale experiments are particularly useful for this kind, especially when performed at an FEL-facility. Beamtime here is extremely scarce and the delay between experiment and publication is notoriously long. A major cause for this delay is the general complexity of the experiments performed.

As an example, consider a pump-and-probe type experiment: In order to get the wanted signal from the sample the X-ray pulse from the FEL source needs to overlap in space and time with the pumping pulse inside the sample. This is made more difficult by several effects:

- The sample response may be dependent of the polarization of the pumping and/or probing pulse.

- There may be significant time and energy jitter in the probing pulse.

- The composition and excitation profile of the sample may vary depending on local sample geometry and may be modified by the probing pulse.

- Detector response may be significantly non-uniform.

...to name some of the issues encountered. Generally some or all of these effects are present at once.

Simulations can in these cases be used to identify distinct footprints of such distortions and thus give the experimenter a means of deconvoluting them from the signal.

We will present studies of this kind along with the newest developments of the McXtrace software package.

9209-11, Session 4

MASH: a framework for the automation of x-ray optical simulations

Peter Sondhauss, Lund Univ. (Sweden)

MASH stands for “Macros for the Automatisation of SHadow”. It allows to run a set of ray-tracing simulations, over a range of photon energies for example, fully automatically. Undulator gaps, crystal angles etc. are tuned automatically. Important output parameters, such as photon flux, photon irradiance, focal spot size, bandwidth, etc. are then directly provided as function of photon energy. A photon energy scan is probably the most commonly requested one, but any parameter or set of parameters can be scanned through as well.

Heat load calculations with finite element analysis providing temperatures, stress and deformations (Comsol) are fully integrated. The deformations can be fed back into the ray-tracing process simply by activating a switch.

MASH tries to hide program internals such as file names, calls to pre-processors etc. so that the user (nearly) only needs to provide the optical setup.

It comes with a web interface, which allows to run it remotely on a central computation server. Hence, no local installation or licenses are required, just a web browser and access to the local network.

Numerous tools are provided to look at the ray-tracing results in the web-browser. The results can be also downloaded for local analysis. All files are human readable text files that can be easily imported into third-party programs for further processing.

All set parameters are stored in a single human-readable file in XML format.

9209-12, Session 4

Acceleration of the ray tracing in xrt with OpenCL

Roman Chernikov, Deutsches Elektronen-Synchrotron (Germany); Konstantin Klementiev, MAX IV Lab. (Sweden)

xrt ray tracing package combines the ease-of-use of the Python scripting with the performance of fast array functions provided by Numpy. Nevertheless if one needs to process millions of rays the computing power of modern CPUs becomes the bottleneck. This is the case where the power of parallel data procession inherent in the GPU can shift the performance to a new level. We have attempted to keep the transparency of the Python code while redirecting the most time consuming operations to the GPU invoking the PyOpenCL extension.

The most performance gain, up to two orders, from hours to minutes scale with the single high-end video card, is observed for the absolutely incoherent ray-wise operations characterized by high computational load and low intensity of device-host memory exchange, for example numerous integration tasks during the undulator flux density distribution calculation, derivation of the ray-surface intersection point at each optical element in the beam path or tracing the propagation of the rays in thick/deformed crystals within the framework of the dynamic diffraction theory.

We demonstrate that the wave field calculations can also be significantly accelerated by the matrix blocking algorithms provided the choice of the problem dimensions is optimal.

9209-13, Session 5

Wolter-I optical systems: from metrology to Point Spread Function *(Invited Paper)*

Daniele Spiga, INAF - Osservatorio Astronomico di Brera (Italy); Lorenzo Raimondi, Sincrotrone Trieste S.C.p.A. (Italy)

One of the problems often encountered in X-ray mirror manufacturing is setting proper manufacturing tolerances to guarantee an angular resolution - often expressed in terms of Point Spread Function (PSF) – as needed by the specific science goal. To do this, we need an accurate metrological apparatus, covering a very broad range of spatial frequencies, and an affordable method to compute the PSF from the metrology dataset. In the past years, a wealth of methods, based on either geometrical optics or the perturbation theory in smooth surface limit, have been proposed to respectively treat long-period profile errors or high-frequency surface roughness. However, the separation between these spectral ranges is difficult do define exactly, and it is also unclear how to affordably combine the PSFs, computed with different methods in different spectral ranges, into a PSF expectation at a given X-ray energy. For this reason, we had a few years ago proposed a method entirely based on the Huygens-Fresnel principle to compute the diffracted field of real Wolter-I optics, including measured defects over a wide range of spatial frequencies. Owing to the shallow angles at play, the computation can be simplified limiting the computation to the longitudinal profiles, neglecting completely the effect of roundness errors. Other authors had already proposed similar approaches in the past, but only in Fraunhofer approximation, therefore they could not be applied to the case of Wolter-I optics, in which two reflections occur in sequence within a short range. The method we suggest is versatile, as it can be applied

to multiple reflection systems, at any X-ray energy, and regardless of the nominal shape of the mirrors in the optical system. The method has been implemented in the WISE code, successfully used to explain the measured PSFs of multilayer-coated optics for astronomic use, and of a K-B optical system in use at the FERMI free electron laser.

9209-14, Session 5

Specification of x-ray mirrors in terms of system performance: a new twist to an old plot *(Invited Paper)*

Valeriy V. Yashchuk, Lawrence Berkeley National Lab. (United States); Liubov Samoylova, European XFEL GmbH (Germany); Igor V. Kozhevnikov, A.V. Shubnikov Institute of Crystallography (Russian Federation)

In the early 1990's [App. Opt. 32(19), 3344-531 (1993)], Church and Takacs pointed out that the specification of surface figure and finish of X-ray mirrors must be based on their performance in the beamline optical system. In the present work, we demonstrate the limitations of specification, characterization, and performance evaluation based on the totally statistical approach, including rms roughness and residual slope variation, evaluated over the spatial frequency bandwidths that are system specific, as well as a more refined statistical description of the surface morphology based on the power spectral density (PSD) distribution. We show that the limitations are fatal, especially, in the case of highly coherent x-ray beams, as ones from Free Electron Lasers (FELs). Physically, the limitations arise due to the deterministic character of the surface profile data for a definite mirror, while the specific correlation properties of the surface are essential for the performance for the entire x-ray optical system. As a possible way to overcome the problem, we treat a method, suggested in [Opt. Eng. 51(4), 046501, 2012] and based on an autoregressive moving average (ARMA) modeling of the slope measurements with a limited number of parameters.
The effectiveness of the approach is demonstrated with a number of examples peculiar to the X-ray optical systems under design at the European FEL. This work was supported by the U. S. Department of Energy under contract number DE- AC02-05CH11231.

9209-15, Session 5

Soft Matter Interfaces beamline at NSLS-II: geometrical ray-tracing vs. wavefront propagation simulations

Mikhail Zhernenkov, Niccolo Canestrari, Oleg Chubar, Elaine DiMasi, Brookhaven National Lab. (United States)

We report on the implications of a design of the Soft Matter Interfaces (SMI) beamline, a long energy range canted in-vacuum undulator (IVU) beamline at NSLS-II, based on geometrical ray-tracing and partially coherent x-ray beam wavefront propagation simulation software packages, namely, SHADOW and SRW. For SHADOW, we employed an SRW-generated source file which precisely simulates the beam size, the shape and the divergence produced by a 2.8 m long IVU with a 23 mm period and allowed us to realistically estimate the beam intensity at the sample positions. We highlight the necessity to use real mirror surface profiles with required slope errors as opposed to built-in sinusoidal SHADOW surface error options. Four x-ray energy cases have been compared: 20358 eV, 10778 eV, 3593 eV, and 2101 eV, under different focusing conditions. We compare the resulting complete beamline simulations performed with both software packages. In particular, we stress that the neglect of the wave-optics effects in geometrical ray-tracing approach results in significant discrepancies in beam spot size, beam shape and the angular divergences which is crucial in determining the future performance of an instrument. We emphasize that even though the partially-coherent wave-optics simulations with the SRW code are currently considerably more CPU-intensive than the fast SHADOW ray-tracing (in the case of the SMI beamline), these simulations are necessary for the verification, further refinement and/or correction of the approximate SHADOW results.

9209-16, Session 5

Partially-coherent wavefront propagation simulations for inelastic x-ray scattering beamline including crystal optics

Alexey Y. Suvorov, Yong Q. Cai, Brookhaven National Lab. (United States); John P. Sutter, Diamond Light Source Ltd. (United Kingdom); Oleg Chubar, Brookhaven National Lab. (United States)

Up to now simulation of perfect crystals optics in the "Synchrotron Radiation Workshop" (SRW) was not available. Thus, accurate modelling of synchrotron beamlines containing multiple-crystal arrangements, such as high-energy-resolution monochromators or high-resolution-diffraction crystal optics, was hindered. A new SRW module for calculating dynamical diffraction from a perfect crystal in the Bragg case overcomes this shortage. We demonstrate successful application of the updated code to the modelling of partially-coherent undulator radiation propagation through the Inelastic X-ray Scattering (IXS) Beamline at the National Synchrotron Light Source II. The IXS beamline contains double-crystal and high energy resolution monochromators, as well as complex optics for the X-ray beam transport and shaping, such as a compound refractive lens and a Kirkpatrick-Baez mirror system, which makes it an excellent case for benchmarking new functionalities of the SRW code. Besides, it has to be mentioned that the IXS experiments are usually very photon-hungry. Therefore accurate evaluation of the photon flux at a sample, using most accurate simulation methods, taking into account parameters of electron beam, details of undulator radiation and x-ray optics is imperative in this case. Here, the results of the simulation are presented and compared with those of other codes.

9209-17, Session 5

Wavefront propagation simulations for a UV/ soft X-ray beamline at NSLS-II

Niccolo Canestrari, Elio Vescovo, Andrew Walter, Oleg Chubar, Brookhaven National Lab. (United States)

Photoelectron spectroscopies greatly benefit from the micron size spot now achievable at modern synchrotron facilities. A small spot makes possible spectro-microscopy measurements while helping to reach the best energy resolution of the electron spectrometer. A case in point is the Electron Spectro-Microscopy (ESM) beamline presently under construction at NSLSII. ESM is designed to make use of undulator radiation beams at variable polarization in a wide photon energy range extending from 15 eV to 1.5 keV. To achieve diffraction-limited micron-scale spot sizes at the sample position is a challenging goal, especially in the UV range. We performed full scale partially coherent wavefront propagation simulations, using SRW code, considering all beamline components: the undulator source (105 mm period 2.8 m long elliptically-polarizing undulator EPU105), the variable groove density grating, the secondary source formed by vertical and horizontal slits and all focusing mirrors. The simulations have been performed for five monochromatic beams ranging from 20 to 100 eV photon energy at the variable polarizations generated at the fundamental harmonic of the undulator. The wavefront propagation results at the sample focal spots are compared to geometrical ray-tracing code SHADOW with an identically defined beamline. The differences between the wavefront propagation and the ray-tracing results are substantial, confirming that the use of wavefront propagation method is crucial for accurate choice of operational parameters and reliable prediction of performances of this beamline.

9209-18, Session 5

Calculation of the instrumental profile function for a powder diffraction beamline used in nanocrystalline material research

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Synchrotron radiation is one of the main tools in the study of nanomaterials, in particular for powder diffraction, which fully exploits the high brilliance, energy selectivity and focusing conditions now routinely available at many beamlines. However, most facilities have been designed for studying conventional materials, whereas a modern approach to nanomaterials requires a complete control of the diffracted signal, and therefore of the optics and general set-up of the beamline [1].

We combine the SHADOW [2] simulation with the calculation of powder diffraction profile from standard materials, into a high-level workflow environment based on the Open Source ORANGE [3] software, allowing us to integrate data analysis fitting software with realistic information [4,5].

We developed algorithms and software tools capable of reproducing optical elements in a realistic form, so to evaluate the effects of aberrations, with the final purpose of reconstructing and representing the instrumental function of the beamline, with the possibility of investigating the role of each separate element.

The results of this work, and in a more general sense the emerging paradigm, could be of interest to many different beamlines currently employed for X-ray spectroscopies. Direct applications will include catalysts, heavily deformed materials and other nanocrystalline systems.

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9209-19, Session 6

Theory of angular dispersive imaging x-ray spectrographs

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A dream x-ray spectrometer is a spectrograph that images x-ray spectra in a single shot with required spectral resolution. Spectrograph is an optical device that disperses photons of different energies into distinct directions and space locations, and takes a snapshot of photons spectra with a spatially sensitive photon detector. Feasibility of hard x-ray spectrographs with a spectral resolution as small as 0.1 meV has been demonstrated recently [1]. Here we present a theory of hard x-ray spectrographs consisting of collimating, angular dispersive, and focusing optics. Single crystal arrangements in asymmetric scattering geometry are used as dispersing elements. Ray transfer matrix technique is applied to propagate x-rays through the optics elements. Several designs of hard x-ray spectrographs with an energy resolution of 1-0.1 meV and a spectral window of 100-10 meV are proposed and analyzed using the theory.

1. Yu. Shvyd’ko, S. Stoupin, K. Mundboth, and J.-H. Kim “Hard-x-ray spectrographs with resolution beyond 100 micro-eV” Phys. Rev. A, 87, (2013) 043835

9209-20, Session 6

Perfect crystal propagator for physical optics simulations with Synchrotron Radiation Workshop

John P. Sutter, Diamond Light Source Ltd. (United Kingdom); Oleg Chubar, Alexey Y. Suvorov, Brookhaven National Lab. (United States)

Until now, a treatment of dynamical diffraction from perfect crystals has been missing in the “Synchrotron Radiation Workshop” (SRW) wavefront propagation computer code despite the widespread use of crystals on X-ray synchrotron beamlines. Now a special “propagator” module for calculating dynamical diffraction from a perfect crystal in the Bragg case has been written in C++, integrated into the SRW C/C++ library and made available for simulations using the Python interface of the SRW. The propagator performs local processing of the frequency-domain electric field in the angular representation. A 2D Fast Fourier Transform is used for changing the field representation from/to coordinate representation before/after applying the crystal propagator. This ensures seamless integration of the new propagator with the existing functionalities of the SRW package, allows for easy inter-operation with existing propagators for other optical elements, and enables the simulation of complex beamlines transporting partially coherent X-rays. The code has been benchmarked by comparison with predictions made by plane-wave and spherical-wave dynamical diffraction theory. Test simulations for a selection of X-ray synchrotron beamlines are also shown.

9209-21, Session 6

Development of spatially-resolved high-resolution x-ray spectroscopy for fusion and light-source research

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One dimensional spatially resolved high resolution x-ray spectroscopy with spherically bent crystals and 2D pixelated detectors is an established technique on magnetic confinement fusion (MCF) experiments world wide for Doppler measurements of spatial profiles of plasma ion temperature and flow velocity. This technique is being further developed for diagnosis of High Energy Density Physics (HEDP) plasmas at laser-plasma facilities and synchrotron/x-ray FEL facilities. Useful spatial resolution (micron scale) of such small-scale plasma sources requires magnification, because of the finite pixel size of x-ray CCDs. A von-Hamos like spectrometer using spherical crystals can provide magnification and uniform sagittal focusing across the x-ray spectrum, and is being tested in laboratory experiments using a tungsten-target microfocus x-ray tube and 13-?m x-ray CCD. Spatial resolution better than 10 ?m has been demonstrated. Good spectral resolution is indicated by small differences (0.02 – 0.1 eV) of measured line widths from published natural linewidths. The validity of analytic throughput equations is tested by consistency of relative intensities of tungsten L?, L?, and L? line intensities, as measured with different crystals, with published values. The tungsten microfocus target size is determined by a knife-edge measurement. Progress and status of MCF and HEDP measurements and the physics basis for these diagnostics will be presented. The status of testing of a 2D imaging microscope using matched pairs of spherical crystals will also be presented. The use of computational x-ray optics codes in development of these instrumental concepts will be addressed.

9209-22, Session 6

Imaging of the photonic crystals with coherent x-rays

Irina I. Snigireva, Anatoly Snigirev, ESRF - The European Synchrotron (France); Victor Kohn, Russian Research Ctr. Kurchatov Institute (Russian Federation)

The method of calculating the transmission of hard x-ray radiation through a perfect and well oriented photonic crystal and propagation of x-ray beam modified by photonic crystal in the free space is developed. The method is based on the approximate solution of the paraxial equation at short distances, from which the recurrent formula for x-ray propagation at longer distances is derived. A computer program for numerical simulation of images of photonic crystals at distances just beyond the crystal up to several millimeters was created. The calculations were performed for Ni inverted photonic crystals with the [111] axis of the face cubic centered structure for the distances up to 0.4 mm with the step of 4 microns. Since the transverse periods of x-ray wave modulation are of several hundred nanometers, the intensity distribution of such a wave is changed significantly on the distance of several microns. This effect is investigated for the first time.

9209-23, Session 6

Modeling of a compound imaging system with a curved monochromator and polycapillary optics

Bushra Kanwal, Alexandru F. Petrescu, Carolyn MacDonald, Univ. at Albany (United States)

Monochromatic x-ray imaging can increase contrast and reduce dose compared to polychromatic x-ray imaging. However, if a conventional x-ray source is used with a flat monochromator crystal, only the small fraction of the beam within the angular bandwidth of the crystal will be diffracted. A doubly curved crystal monochromator collects and focuses x rays from a large solid angle, making more efficient use of a conventional x-ray source, and producing a focused monochromatic x-ray beam. However, the shape of the beam after focal spot of the bent crystal optic is not conducive to imaging. A combination of a bent crystal optic followed by a focusing polycapillary optic can be used to monochromatize and focus x rays to a small spot to perform monochromatic x-ray imaging. The character of the beam after the polycapillary optic is somewhat complex. A Monte Carlo ray-tracing simulation model has been developed which takes into account optics defects for both optics. Comparison is made to measurements of focal spot sizes, angular divergence, and image quality parameters including resolution and contrast.

9209-24, Session 7

Computational x-ray phase imaging *(Invited Paper)*

Jonathan C. Petruccelli, Carolyn MacDonald, Univ. at Albany (United States); George Barbastathis, Massachusetts Institute of Technology (United States) and SMART-Singapore MIT Alliance for Research & Technology (Singapore); Adam Pan, Massachusetts Institute of Technology (United States); Lei Tian, Univ. of California, Berkeley (United States); Kelli Zhu, Massachusetts Institute of Technology (United States); Sajid Bashir, Sajjad Tahir, Univ. at Albany (United States)

The goal of X-ray imaging is to obtain information about an object's properties from intensity variations across a detector. These properties can be characterized in terms of a complex-valued refractive index distribution throughout the object's volume, whose imaginary and real parts describes both the attenuation of the incident X-ray beam and the phase imparted to it, respectively, from passage through the sample. In conventional radiography, only the attenuation of the primary beam is measured. Since many materials exhibit similar attenuation, phase imaging can often provide additional discrimination. In addition, combining phase imaging with computational tomography allows the refractive index to be described throughout the object's volume. Phase imaging techniques are often heavily computational, since the intensity measurement at a detector is not generally directly proportional to phase. Instead, a model is developed to predict the intensity from the underlying phase in a given measurement scheme. This model can then be computationally inverted to recover the phase. Computational inversion presents challenges not faced in traditional radiography, such as amplification of noise and introduction of artifacts. We discuss recent work on several phase imaging methods that rely on propagation to generate phase contrast at the detector, either through free-space propagation or the use of grids. In each case, the forward model and inversion techniques are presented along with methods developed to handle noise and other artifacts in the phase reconstructions. Single projection phase imaging and phase tomography algorithms are described. Bench-top X-ray systems used for phase imaging are described and phase measurements are presented from several such systems.

9209-26, Session 7

The finite-difference simulation of x-rays propagation through the system of lenses

Sergey P. Kshevetskii, Immanuel Kant State Univ. of Russia (Russian Federation); Pawel R. Wojda, Gdansk Univ. of Technology (Poland)

In our theoretical study we consider X-rays propagation through a system of lenses. The problem of calculation of image and focusing is the subject of investigation. Finite-difference scheme for solving equation of high-frequency electromagnetic waves is derived. New approach not used until now is presented. This method does not lose in efficiency to another methods which have been developed until now, and is better in some cases. This method is applied to the problem of X-rays propagation in porous beryllium and the results is in good coincidence with an experiment. Examples of simulation of X-rays propagation through the system of lenses and propagation X-rays in porous beryllium is demonstrated.

9209-27, Session 7

Contrast enhancement of propagation based x-ray phase contrast imaging

Adam Pan, Ling Xu, Massachusetts Institute of Technology (United States); Jonathan C. Petruccelli, Univ. at Albany (United States); Rajiv Gupta, Massachusetts General Hospital (United States); George Barbastathis, Massachusetts Institute of Technology (United States)

We demonstrate a quantitative X-ray phase contrast imaging (XPCI) technique derived from propagation based retrieval. In this method, the absorption and phase components are assumed to be correlated, and the Transport of Intensity Equation (TIE) is solved. The experimental setup is simple compared to other XPCI techniques; the only requirements are a micro-focus X-ray source of sufficient temporal coherence and an X-ray detector of sufficient spatial resolution. This method was demonstrated in three scenarios, the first of which was identifying an index-matched sphere. A rubber and nylon sphere were immersed in water and imaged. While the rubber sphere can be plainly seen on a radiograph, the nylon sphere was only visible in the phase reconstruction. Next, the technique was applied to differentiating liquid samples. In this scenario, three liquid samples (acetone, water, and hydrogen peroxide) were analyzed using

both conventional computed tomography (CT) and phase contrast CT. While conventional CT was capable of differentiating between acetone and the other two liquids, it failed to distinguish between water and hydrogen peroxide; only phase CT was capable of differentiating all three samples. Finally, the technique was applied to CT imaging of a biological artery specimen. This scenario demonstrates the increased sensitivity to soft tissue compared to conventional CT, and also illustrates some drawbacks of the method, which will be the target of future work. In all cases, the signal-to-noise ratio of phase contrast is greatly enhanced relative to conventional attenuation-based imaging.

9209-28, Session 8

Quantitative phase imaging using dual wavelength x-rays

Ling Xu, Massachusetts Institute of Technology (United States); Yongjin Sung, Massachusetts General Hospital (United States); Adam Pan, Massachusetts Institute of Technology (United States); Rajiv Gupta, Massachusetts General Hospital (United States); George Barbastathis, Massachusetts Institute of Technology (United States)

Much recent work has been devoted to quantitative phase imaging in the soft x–ray band, since it is now broadly recognized that phase offers valuable information for medical and security applications where absorption alone is insufficient. Of the prominent methods, propagation based (or in-line) phase imaging is emerging as an experimentally practical alternative to the more widely used interferometric and analyzer based X-ray phase imaging systems. In in-line X-ray phase imaging, decoupling absorption from phase features requires multiple axially displaced intensity measurements. Such maneuvers, however, are prone to misalignment errors and increase data acquisition time. Techniques based on a single image exist but require assumption of weak or uniform absorption. We present an analytical method for simultaneously retrieving phase and absorption using images obtained from X-ray exposures at two different energies. We specifically generate X-rays at two different tube voltages and use a filter for high band separation. Our approach takes advantage of the change in diffraction pattern associated with the change in wavelength. We demonstrate this approach experimentally using a micro-focus source and with spheres of various materials. We show that the retrieved phase is quantitative and allows us to distinguish between materials. We further implement this technique in tomography by imaging a biological sample with both phase (soft tissue) and attenuation elements (calcification) to show independent retrieval of absorption and phase.

9209-29, Session 8

3D x-ray reconstruction using lightfield imaging

Murat Tahtali, Sajib K. Saha, Andrew J. Lambert, Mark R. Pickering, UNSW@ADFA (Australia)

Existing Computed Tomography (CT) systems require full 360? rotation projections. Using the principles of lightfield imaging, only 4 projections under ideal conditions can be sufficient when the object is illuminated with multiple-point X-ray sources. The concept was presented in a previous work with synthetically sampled data from a synthetic phantom. Application to real data requires precise calibration of the physical set up. This current work presents the calibration procedures using a physical 3D phantom consisting of simple geometric shapes. The crucial part of this process is to determine the effective distances of the X-ray paths, which are not possible or very difficult by direct measurements. Instead, they are calculated by tracking the positions of fiducial markers under prescribed source and object movements. Determination of minimal sampling parameters for a targeted reconstruction resolution using ART will be attempted. The results will be compared with conventional CT scanning performed on the same phantom with the same apparatus.

9209-30, Session 8

Developments of x-ray grating imaging and trying of multiple information fusion

Yueping Han, Li Ruihong, North Univ. of China (China)

The present paper reviews the X-ray grating imaging systems at home and abroad from the aspects of technological characterizations and the newest researching focus. First, not only the imaging principles and the frameworks of the typical X-ray grating imaging system based on Talbot-Lau interferometry method, but also the algorithms of retrieving the signals of attenuation, refraction and small-angle scattering are introduced. Second, the system optimizing methods are discussed, which involves mainly the relaxing the requirement of high positioning resolution and strict circumstances for gratings and designing large field of view with high resolution. Third, two and four-dimensional grating-based X-ray imaging techniques are introduced.

For the three kinds of information (attenuation, refraction and scattering) synchronously obtained by the X-ray grating imaging setup, the attenuation image almost can't see the weak absorption material details, while the dark field imaging and phase contrast imaging is not sensitive to heavy absorption material, so any imaging mode is hard to obtain the global structures of object tested with high dynamic range, for example, bones and tendons, teeth and gums, chip pins and its basal. In this paper, we tried multiple information fusion technology with the methods of wavelet transform and Laplace transform for three information obtained synchronously.

Conference 9210: X-Ray Free-Electron Lasers: Beam Diagnostics, Beamline Instrumentation, and Applications II

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9210-1, Session 1

SASE3: soft x-ray beamline at European XFEL *(Invited Paper)*

Daniele La Civita, Natalia Gerasimova, Maurizio Vannoni, Harald Sinn, European XFEL GmbH (Germany)

The European XFEL in Hamburg will be comprised of a linear accelerator and three Free-Electron-Laser beamlines (SASE1, SASE2 and SASE3) covering the energy range from 250 eV to 24 keV. It will provide up to 2700 pulses in trains of 600 microsecond duration at a repetition rate of 10 Hz.

SASE3 beamline is the soft X-ray beamline (0.25-3 keV) and delivers photon pulses to SQS (Small Quantum System) and SCS (Spectroscopy & Coherent Scattering) experiments. The beamline is able to operate in both monochromatic and non-monochromatic mode. The latter provides the inherent FEL bandwidth at higher intensities. The beamline from photon source to experimental station is about 450m long. The length of the beamline is related to the optics single-shot-damage issue. The almost diffraction-limited beam is propagated along the beamline with very long (up to 800mm clear aperture), cooled (with eutectic bath) and super-polished (50nrad RMS slope error and less than 3nm PV residual height error) mirrors. The VLS-PGMonochromator covers the entire beamline energy range and its optical design is guided by the optimization of the energy resolving power, the minimization of the pulse broadening and the maximization of optics damage tolerance. Grating substrates are 530mm long, eutectic cooled and present outstanding surface quality. The VLS parameters of the blazed profile are also a real challenge under manufacturing and measuring point of view. Adaptive optics in the horizontal (the second offset mirror) and vertical (monochromator premirror) plane are foreseen in the optical layout to increase the beamline tunability and to preserve the highly coherent beam properties.

Beamline optical design, expected performance and also mechanical aspects of main beamline components are reported.

9210-2, Session 1

The experience of the FERMI@Elettra photon beam transport and diagnostics system (PADReS) during three years of continuous support of machine and user experiments: achievements, lessons learned, and future upgrades

Marco Zangrando, Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and IOM-CNR (Italy)

The FERMI FEL facility has begun delivering photons in 2011, becoming in late 2012 the first seeded facility open to external users worldwide. Since then, several tens of experiments have been carried out on the three operative endstations LDM, DiProI, and EIS-TIMEX. Starting from the commissioning phase, the transport and diagnostics system (PADReS) has been continuously developed and upgraded, becoming the indispensable interface between the machine and the experimental chambers. Moreover, PADReS itself has served as an active player for several machine studies as well as for various state-of-the-art experiments. In particular, some elements of PADReS have become key features to perform cutting edge experiments: the online energy spectrometer, the active optics refocusing systems, the split and delay line, and so on. For each of them the peculiar advantages will be described showing the actual implementation in the experiments.

The experience gathered so far in fulfilling the needs of both machine and experimental physicists will be discussed, with particular emphasis on the solutions adopted in different scenarios. Recurrent requests and major difficulties will be reported so to give a glimpse about the standard tasks to be solved when preparing new and demanding experiments.

Finally, some ideas and near-future improvements will be presented and discussed.

9210-3, Session 1

Status and perspectives of experimental platform at SACLA

Yuichi Inubushi, Kensuke Tono, Tadashi Togashi, Tetsuo Katayama, Japan Synchrotron Radiation Research Institute (Japan); Kanade Ogawa, Shigeki Owada, Makina Yabashi, RIKEN (Japan)

SACLA has successfully generated brilliant, femtosecond X-ray pulses. In this presentation, I will talk about status of the experimental platform at SACLA, including X-ray focusing devices, synchronized optical laser systems, measuring instruments and their recent applications. Also, I will present perspectives of facility upgrade such as introduction of self-seeded XFEL and construction of a new beamline.

9210-4, Session 1

First very positive soft x-ray self-seeding results at LCLS *(Invited Paper)*

Daniele Cocco, SLAC National Accelerator Lab. (United States)

After the successful demonstration of the hard X-ray self-seeding at LCLS, an effort to build a system for working in the soft X-ray region was carried on and successfully completed. A grating monochromator, placed in middle of the undulators selects a narrow bandwidth to “seed” the downstream section of undulators. The narrowed bandwidth signal is then amplified to saturation in the downstream section of the undulators. In December 2013, for the first time in the world, we obtained a self-seeding beam out of the LCLS undulators. The measured bandwidth (in that and further commissioning shifts) was narrower than the target project goal. A laser like beam with good energy stability, narrow bandwidth and very high pulse energy was therefore, since then, available in the soft X-ray range (from 500 to 1200 eV) at LCLS. The boosting results and beam characterization will be presented in some details, and a discussion on the achievable experiment (already performed or not) will be also included

9210-5, Session 2

Control of a 45-cm long x-ray deformable mirror with either external or internal metrology *(Invited Paper)*

Lisa A. Poyneer, Thomas J. McCarville, Tommaso Pardini, David W. Palmer, Lawrence Livermore National Lab. (United States); Audrey D. Brooks, Northrop Grumman Xinetics (United States)

We present our most recent results in controlling a 45-cm long x-ray deformable mirror. Its surface figure is measured with high-precision visible-light interferometry. Using this metrology and custom control algorithms, we have actuated the x-ray deformable mirror and flattened its entire surface to as good as 0.7 nm rms controllable figure error. The mirror's figure, as well as the overall sphere, changes with time due to small temperature changes in the laboratory and

non-linear effects in the PMN actuators. We plan to use feedback from the mirror's internal temperature sensors and strain gauges to maintain its figure and sphere, independent of external metrology. LLNL-ABS-649074.

9210-6, Session 2

Beam branching system for single-shot spectral and timing analysis of XFEL pulses

Tetsuo Katayama, Japan Synchrotron Radiation Research Institute (Japan); Petri Karvinen, Ismo J. Vartiainen, Anni Partanen, Paul Scherrer Institut (Switzerland); Kanade Ogawa, RIKEN (Japan); Tadashi Togashi, Yuichi Inubushi, Kensuke Tono, Japan Synchrotron Radiation Research Institute (Japan); Christian David, Paul Scherrer Institut (Switzerland); Makina Yabashi, RIKEN (Japan)

The advent of x-ray free electron laser (XFEL) provides great capabilities in a variety of scientific fields, such as ultrafast chemistry, nonlinear physics, and structural biology. For the advanced utilization of XFELs, it is important to diagnose XFEL in the single-shot scheme.

We are developing the single-shot beam diagnostic system using a transmission grating as a beam splitter. The grating splits x-ray beam into several branches. The first order-diffracted beams are utilized for the single-shot spectrometer [1,2] and the timing monitor between XFELs and an optical laser [3]. The instruments are designed to avoid the interference of the 0th order transmission beam so as to perform experiments downstream.

We present the results of the proof-of-principle experiment to evaluate the performance of the grating splitter. We then introduce a design of the system that will be installed in the beamline at SACLA.

[1] M. Yabashi, et al., Phys. Rev. Lett. 97, 084802 (2006).

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9210-7, Session 2

High-resolution single-shot spectral monitoring of hard XFEL radiation

Mikako Makita, Petri Karvinen, Paul Scherrer Institut (Switzerland); Diling Zhu, SLAC National Accelerator Lab. (United States); Jan Grünert, European XFEL GmbH (Germany); Sebastian Cartier, Paul Scherrer Institut (Switzerland); Yiping Feng, SLAC National Accelerator Lab. (United States); Julia H. Jungmann, Pavle Juranic, Paul Scherrer Institut (Switzerland); Henrik T. Lemke, SLAC National Accelerator Lab. (United States); Aldo Mozzanica, Paul Scherrer Institut (Switzerland); Silke Nelson, SLAC National Accelerator Lab. (United States); Luc Patthey, Paul Scherrer Institut (Switzerland); Marcin Sikorski, Sanghoon Song, SLAC National Accelerator Lab. (United States); Christian David, Paul Scherrer Institut (Switzerland)

The self-amplified spontaneous emission (SASE) leads to a fluctuating spiky spectrum, which by its stochastic nature cannot be predicted. In order to eliminate the effects of these fluctuations from the data collected by experimenters, XFEL facilities face the challenge to provide spectral measurements on each individual pulse, with sufficient resolution, and without interfering with the experiment itself. So far, no method has been established that fulfils all these requirements.

Within a collaboration of several research institutions, we have demonstrated to develop and test a novel type of noninvasive, single-shot hard x-ray spectral monitor. The instrument is based on nanostructured diamond diffraction gratings to split part of the beam and to diffract a small fraction it onto a dispersive bent Bragg crystal, and to record the Bragg reflection with a fast-framing strip detector. This geometry combines the high resolution of a crystal-based analyzer with the robustness and low interference of the grating spectrometer.

We have established the properties of this scheme regarding the X-ray energy range between 4.4 – 8.4keV, with measured energy resolution of 0.1eV-0.2eV on the detector, and its stability through 120Hz LCLS full beam. This single shot spectral monitoring provides information needed to optimize the accelerator operation parameters, for instance for the commissioning of seeding schemes or to stabilize the emission. This successful result further suggests the possibility to permanently implement this scheme in the tunnel of XFEL sources to provide single-shot spectra as reference required in user experiments.

9210-8, Session 3

Development of split-delay x-ray optics using Si(220) crystals at SACLA *(Invited Paper)*

Taito Osaka, Takashi Hirano, Osaka Univ. (Japan); Makina Yabashi, RIKEN (Japan); Yasuhisa Sano, Osaka Univ. (Japan); Kensuke Tono, Yuichi Inubushi, Japan Synchrotron Radiation Research Institute (Japan); Takahiro Sato, Tokyo Univ. (Japan); Kanade Ogawa, RIKEN (Japan); Satoshi Matsuyama, Osaka Univ. (Japan); Tetsuya Ishikawa, RIKEN (Japan); Kazuto Yamauchi, Osaka Univ. (Japan)

The successful operation of x-ray free-electron lasers (XFELs) such as SPring-8 Angstrom Compact free-electron LAser (SACLA) in Japan provides novel x-ray sources with great properties such as an unprecedented power density, full transverse coherence, and a duration down to a few femtoseconds, which offer great promise for exploring new scientific possibilities in ultrafast science with hard x rays. A split-delay optical system, which has a potential to provide two replica XFEL pulses with time delay precisely controlled, will play an important role for XFEL pump–XFEL probe experiments and x-ray photon correlation spectroscopy from femtosecond to nanosecond time scale. High throughput and wide ranges of photon energy and delay time are necessary properties to accept various experiments. Although such a system using Si(511) crystals has been reported, its throughput is poor because of the narrow energy acceptance, and it is based on vertical-scattering geometry (i.e., acceptable photon energy is limited). We proposed another system using Si(220) crystals, which have 7 times wider energy acceptance than that of Si(511) crystals, and a pair of channel-cut crystals to simplify the system and alignment procedure. So far, we have developed essential optical devices of the system, sub 10-??m-thick Si(220) crystals and channel-cut crystals, with high diffraction quality by using an etching technique based on atmospheric-pressure plasma. Here we report the current status of our system and future applications at SACLA.

9210-9, Session 3

Time-delayed beam splitting with energy separation of x-ray channels

Yuri V. Shvyd'ko, Yuri P. Stetsko, Gregory B. Stephenson, Argonne National Lab. (United States)

Yuri P. Stetsko, Yuri V. Shvyd'ko, G. Brian Stephenson\

A time-delayed beam splitting method is introduced based on the energy separation of x-ray photon beams [1]. It is implemented and theoretically substantiated on an example of an x-ray optical scheme similar to that of the classical Michelson interferometer. The splitter/mixer uses Bragg-

case diffraction from a thin diamond crystal. Another two diamond crystals are used as back-reflectors.

Because of energy separation and a minimal number (three) of optical elements, the split-delay line has high efficiency and is simple to operate. Due to the high transparency of diamond crystal, the split-delay line can be used in a beam sharing mode at x-ray free-electron laser facilities. The delay line can be made more compact by adding a fourth crystal.\

1. Yuri P. Stetsko, Yuri V. Shvyd'ko, G. Brian Stephenson, Appl. Phys. Lett., 103, 173508 (2013)

9210-10, Session 3

A hard x-ray split- and delay-unit for the High-Energy Density instrument at the European XFEL

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For the High-Energy Density (HED) beamline at the European XFEL an x-ray split- and delay-unit (SDU) is built for photon energies from 5 keV up to 20 keV. Being part of the HED instrument, the SDU will enable the investigation of matter under high-energy density conditions via time-resolved x-ray pump / x-ray probe experiments on a femtosecond to picosecond time scale. The set-up is based on wavefront splitting that has successfully been implemented at an autocorrelator at FLASH. The x-ray FEL pulses will be split by a sharp edge of a multilayer mirror. Both partial beams will then pass variable delay lines. For different wavelengths the angle of incidence onto the multilayer mirrors and in consequence the whole beam path will be adjusted in order to match the Bragg condition. This requires an angular reproducibility of all mechanical motions of better than 100 µrad, which has been demonstrated successfully. Depending on the Bragg angle corresponding to the specific photon energy maximum delays between +/- 2.5 ps at h? = 20 keV and up to +/- 33 ps at h? = 5 keV will be possible. The time-dependent wave-optics simulations have been performed using SRW software. The XFEL radiation was simulated using an output of the time-dependent SASE code FAST. Main features of the optical layout, including diffraction on the splitter edge, and height- and slope-errors of the mirrors were taken into account. The influences of these effects on the prospects to characterize spatial-temporal properties of FEL pulses are analyzed.

9210-11, Session 3

A multiple split-and-delay line for x-ray pump-probe experiments *(Invited Paper)*

Christian David, Petri Karvinen, Paul Scherrer Institut (Switzerland); Marcin Sikorski, Sanghoon Song, SLAC National Accelerator Lab. (United States); Ismo J. Vartiainen, Christopher J. Milne, Aldo Mozzanica, Yves Kayser, Ana Diaz, Istvan Mohacsi, Paul Scherrer Institut (Switzerland); Gabriella A. Carini, Sven C. Herrmann, SLAC National Accelerator Lab. (United States); Elina Färm, Mikko Ritala, Univ. of Helsinki (Finland); David M. Fritz, Robert Aymeric, SLAC National Accelerator Lab. (United States)

Among the key applications of x-ray free-electron lasers are ultrafast time-resolved studies on the dynamics of matter by observing its response to a fast excitation pulse. Usually, the sample's dynamics are obtained by repeating multiple measurements at different delay times with fs accuracy. This severe limitation implies that the sample returns to an identical ground state after each excitation. We present a novel approach that can provide a time trace of responses following a single excitation pulse. It is based on an arrangement of diffraction gratings that splits parts of the main pump beam and recombines them at the sample. More than 10 probe beams were generated for each pump pulse, with delays ranging from 20 to 1200 fs. As the delays are determined by the geometrical dimensions, the setup is free of timing jitter and time zero is known with fs precision. In a first diffraction experiment performed at 4.5 keV photon energy at the XCS experimental station of LCLS we demonstrate that the method can be applied to the investigation of destructive processes.

9210-12, Session 3

Silicon mirrors for high-intensity x-ray pump-and-probe experiments

Tommaso Pardini, Lawrence Livermore National Lab. (United States); Sebastien Boutet, SLAC National Accelerator Lab. (United States); Tilo Doeppner, Luke B. Fletcher, Lawrence Livermore National Lab. (United States); Dennis F. Gardner Jr., JILA (United States); Randolph M. Hill, Mark S. Hunter, Lawrence Livermore National Lab. (United States); Jacek Krzywinski, Marc Messerschmidt, SLAC National Accelerator Lab. (United States); Arthur E. Pak, Lawrence Livermore National Lab. (United States); Florian Quirin, Klaus Sokolowski-Tinten, Univ. Duisburg-Essen (Germany); Garth J. Williams, SLAC National Accelerator Lab. (United States); Stefan P. Hau-Riege, Lawrence Livermore National Lab. (United States)

An all-x-ray pump-and-probe capability is needed for the Free Electron Laser (FEL) community. A possible implementation involves the use of an x-ray mirror downstream of the sample to back-reflect the pump beam onto itself. We exposed silicon single crystals, a candidate for this hard x-ray back-reflector, to the hard x-ray beam of the Linac Coherent Light Source (LCLS, SLAC National Acceleration Laboratory) to assess its suitability. We found that Silicon is a suitable mirror material, but its reflectivity at high x-ray fluences is somewhat unpredictable. We attribute this behavior to x-ray-induced local damage in the sample, which we have characterized post-mortem via micro-diffraction analysis. Based on these results, we propose a strategy to reduce local damage, and therefore achieve reproducible values of reflectivity, by using a newly engineered silicon-based mirror. Preliminary results suggest that the new mirror geometry yields reproducible Bragg reflectivity at high x-ray fluences, promising a path forward for Silicon single crystals as x-ray back-reflectors.

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9210-14, Session 4

Spectrometer for single-shot X-ray emission and photon diagnostics

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Cesare Grazioli, Sincrotrone Trieste S.C.p.A. (Italy); Monica de Simone, Lab. Nazionale TASC (Italy); Paola Finetti, Sincrotrone Trieste S.C.p.A. (Italy); Andrea Di Cicco, Fabio Iesari, Univ. degli Studi di Camerino (Italy); Salvatore Stagira, Politecnico di Milano (Italy); Luca Poletto, IFN-CNR LUXOR Lab. (Italy); Carlo Callegari, Erika Giangrisostomi, Riccardo Mincigrucci, Emiliano Principi, Elettra-Sincrotrone Trieste, I-34149 Basovizza (Italy)

The increasing availability, for the user community, of light sources of IV generation (Free Electron Lasers), pushes for the development of measuring instrumentation able to fully exploit the peculiar characteristics of these sources. The high brilliance opens the way to the possibility of to investigate non linear phenomena characterized by a low cross section; the pulsed temporal shape forces to treat each pulse as a single physical experiment. These two considerations have driven the work here presented: an extremely compact spectrometer for photon-in photon-out experiments. The device is interfaced to the target area chamber with a CF 150 flange, the energy range covers the 30 – 800 eV region using two interchangeable gratings. The aperture of the entrance slit is remotely adjustable from 30 um up to 1.0 mm. The compactness of the slit (about 5 cm) permits to place it very close to the sample, increasing the collected photon flux. To minimize the photon absorption in the travel from the generation point to the detector, a metallic shield connects the slit to the region where the detector is placed; this region is separately pumped, assuring a vacuum level of the order of 10^-5 mbar even in case of gas phase experiments. To cover the whole spectral region the detector is mounted on a movable translation stage. We present the first experimental results obtained using this instrument in inelastic scattering experiments both at the synchrotron beamline ELETTRA (TS, Italy) and in the Free Electron Laser FERMI@ELETTRA. Solid and gaseous targets have been tested to validate the two different experimental working conditions.

9210-15, Session 4

The LCLS Matter in Extreme Conditions (MEC) instrument

Philip A Heimann, Hae Ja Lee, Bob Nagler, Eric C. Galtier, Eduardo Granados, Brice Arnold, Jing Yin, SLAC National Accelerator Lab. (United States)

The LCLS Matter under Extreme Conditions (MEC) instrument has been in operation since April 2012. The instrument is comprised of x-ray optics and diagnostics, a large target chamber and nanosecond and femtosecond laser systems. The x-ray focusing is accomplished by Be lenses. The nanosecond laser system delivers 15 J pulses from each of two arms. The femtosecond laser system provides 120 mJ pulses. An upgrade of the femtosecond laser system is underway first to an energy of 1 J and then to 7 J. Diagnostics include forward and backward scattering x-ray spectrometers, a Velocity Interferometer System for Any Reflector (VISAR) and area detectors for x-ray diffraction. A multiplexing method, to provide beamtime at two instruments, has been developed by translating a mirror into and out of the x-ray beam at the repetition rate of the nanosecond laser system. Examples of scattering, diffraction and imaging experiments at MEC will be presented.

9210-16, Session 4

The challenges of mechanical design for the LCLS Matter in Extreme Conditions (MEC) instrument

Brice Arnold, Eric C. Galtier, Philip A. Heimann, Hae Ja Lee, Bob Nagler, Jing Yin, Eduardo Granados, SLAC National Accelerator Lab. (United States)

The MEC instrument was the last instrument to come on-line for SLAC LCLS in 2012. Since then, we have successfully supported almost two dozen experiments including a couple of optical-laser-only experiments. Each experiment has presented itself with various mechanical design challenges. Much of the hardware that has been designed for the sample environment is unique to the experimental layouts as specified by each individual user group. With one of the largest sample chambers at SLAC, measuring roughly 2 meters in diameter by 1 meter high (internal volume); we have the luxury of having an incredibly versatile experimental environment. We are challenged with meeting the specifications and needs of the users in a timely manner as well as designing our hardware to be both simple and versatile for future applications. The expansion of the laser capabilities of the instrument, the ability to support a multitude of samples, and the flexibility to utilize new detectors and spectrometers, also present mechanical design challenges.

9210-17, Session 4

Diverse application platform for hard x-ray diffraction in SACLA (DAPHNIS)

Kensuke Tono, Japan Synchrotron Radiation Research Institute (Japan); So Iwata, Rie Tanaka, Eriko Nango, RIKEN (Japan); Mamoru Suzuki, Osaka Univ. (Japan); Changyong Song, Jaehyun Park, RIKEN (Japan); Takashi Kameshima, Japan Synchrotron Radiation Research Institute (Japan); Shun Ono, RIKEN (Japan); Yasumasa Joti, Japan Synchrotron Radiation Research Institute (Japan); Takaki Hatsui, Makina Yabashi, RIKEN (Japan)

We have developed a diffraction-experiment platform, DAPHNIS, for hard x-ray free electron laser (XFEL) of SPring-8 Angstrom Compact free electron LAser (SACLA). It has wide applicability by combining a compact chamber with a variety of sample injectors and detectors. The operation under atmospheric pressure (helium atmosphere) is particularly favorable for liquid samples, which are often used in experiments of the diffraction-before-destruction style; for example, serial femtosecond crystallography (SFX) and wide-angle solution scattering.

DAPHNIS has been applied to protein SFX at SACLA. Suspension of micrometer-size protein crystals is injected to the focal point of the KB mirrors at the 3rd experimental hutch, where a focused XFEL beam with 1-2 micrometer is provided. Diffraction images are recorded at 30 Hz with the multi-port CCD detector (MPCCD). The ultrashort pulse duration of XFEL (<10 fs) can allow us to take diffraction patters from damage-free crystals.

We will show the design of DAPHNIS and results of test SFX experiments at SACLA.

9210-18, Session 4

Time-delay-compensated monochromator for FEL beamlines

Luca Poletto, IFN-CNR LUXOR Lab. (Italy); Fabio Frassetto, Consiglio Nazionale delle Ricerche (Italy) and Istituto di Fotonia e Nanotecnologie (Italy); Elke Ploenjes, Marion Kuhlmann, Deutsches Elektronen-Synchrotron (Germany)

The consolidation of the FEL sources, from experimental machines to reliable sources, opens now the door to the development of more sophisticated beam-lines (B-Ls). In particular, due to the intrinsic multi-harmonics generation process, one of the most demanded B-L feature is the possibility to monochromatize the FEL beam even beyond the intrinsic FEL resolution. Inherited from the synchrotron experience, grating monochromators are used in FEL B-Ls, both at FLASH and LCLS. Unfortunately, especially for operation in the extreme-ultraviolet region of FLASH, the monochromator response strongly affects the FEL pulse duration.

Here we present the design of a Time-Delay-Compensated Monochromator (TDCM) explicitly designed for extreme-ultraviolet FEL sources, in particular the upcoming FLASH2. The design originates

from the variable-line-spaced (VLS) grating monochromator by adding a second grating to compensate for the pulse-front tilt given by the first grating after the diffraction. The covered spectral range is 6-60 nm, the spectral resolution is in the range 1000 – 3000, while the residual temporal broadening is lower than 15 fs. Accounting for typical FLASH2 divergences, the grazing angles on the different optics have been chosen so that the lengths of the mirrors and gratings are respectively less than 500 mm and 300 mm. The estimate BL efficiency is discussed. The proposed design: 1) minimizes the number of optical elements, since just one grating is added with respect to a standard VLS monochromator B-L; 2) guarantees high focusing properties in the entire spectral range; 3) requires simple mechanical movements, since only rotations are needed to perform the spectral scan.

9210-19, Session 5

Femtosecond-scale x-ray FEL diagnostics with the LCLS X-band transverse deflector *(Invited Paper)*

Timothy J. Maxwell, Yuantao Ding, Zhirong Huang, SLAC National Accelerator Lab. (United States); Christopher Behrens, Deutsches Elektronen-Synchrotron (Germany); Patrick Krejcik, SLAC National Accelerator Lab. (United States); Agostino Marinelli, Luciano Piccoli, Daniel Ratner, SLAC National Accelerator Laboratory (United States)

Analysis of shot-to-shot, lasing-induced changes of the longitudinal electron beam phase space has proven invaluable for fs-scale reconstruction of otherwise difficult to measure x-ray FEL pulse profiles. In this talk, we report on measurements following the recent installation of an X-band transverse deflecting mode cavity at the LCLS. Images of the electron beam's longitudinal phase space are benchmarked to an unprecedented 1 to 3 fs RMS time resolution, enabling a host of new online beam and FEL diagnostic studies. The range of validity for the applied FEL pulse profiling technique has been rigorously inspected, illuminating its limitations. Phenomena impacting the performance of an x-ray FEL have also been observed. The LCLS x-band transverse deflector is generally demonstrated as a powerful, single-shot, x-ray diagnostic in support of both user experiments and machine improvement studies.

9210-22, Session 5

Polarization measurement of free electron laser pulses in the VUV generated by the variable polarization source FERMI

Paola Finetti, Enrico M. Allaria, Bruno Diviacco, Carlo Callegari, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Benoit Mahieu, Ecole Nationale Supérieure de Techniques Avancées (France); Jens Viefhaus, Deutsches Elektronen-Synchrotron (Germany); Marco Zangrando, Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and CNR Istituto Officina dei Materiali (Italy); Giovanni De Ninno, Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and Univ. of Nova Gorica (Slovenia); Guillaume Lambert, Ecole Nationale Supérieure de Techniques Avancées (France); Eugenio Ferrari, Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and Univ. degli Studi di Trieste (Italy); Jens Buck, European XFEL GmbH (Germany); Markus Ilchen, European XFEL GmbH (Germany) and SLAC National Accelerator Lab. (United States); Boris Vodungbo, Deutsches Elektronen-Synchrotron (Germany) and Univ. of Nova Gorica (Slovenia); Nicola Mahne, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Cristian Svetina, Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and Univ. degli Studi di Trieste (Italy); Carlo Spezzani, Simone Di Mitri, Giuseppe Penco, Mauro Trovo, William M. Fawley, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Primoz Rebernik, David Gauthier, Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and Univ. of Nova Gorica (Slovenia); Cesare Grazioli, Univ. of Nova Gorica (Slovenia) and Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and Lab. Nazionale TASC (Italy); Marcello Coreno, Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and Consiglio Nazionale delle Ricerche (Italy); Barbara Ressel, Univ. of Nova Gorica (Slovenia); Antti Kivimäki, Lab. Nazionale TASC (Italy); Tommaso Mazza, European XFEL GmbH (Germany); Leif Glaser, Frank Scholz, Joern Seltmann, Deutsches Elektronen-Synchrotron (Germany); Patrick Gessler, Jan Grünert, Alberto De Fanis, Michael Meyer, European XFEL GmbH (Germany); A. Knie, Univ. Kassel (Germany); Stefan P. Moeller, SLAC National Accelerator Lab. (United States); Lorenzo Raimondi, Flavio Capotondi, Emanuele Pedersoli, Oksana Plekan, Miltcho B. Danailov, Alexander A. Demidovich, Ivaylo Petrov Nikolov, Alessandro Abrami, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Julien Gautier, Ecole Nationale Supérieure de Techniques Avancées (France); Jan Lüning, UPMC Sorbonne Univ. (France); Philippe Zeitoun, Ecole Nationale Supérieure de Techniques Avancées (France); Luca Giannessi, Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and ENEA (Italy)

The last decade was characterized by a tremendous progress in the development and achievement of short wavelength free electron lasers and FERMI is the first FEL facility operated for users experiments in seeded mode. Another prominent feature that distinguishes FERMI from other short-wavelength FEL is the possibility to control the polarization of the radiation. This type of control is achieved by using specially designed undulators that can change the trajectory of the electron beam in both the vertical and the horizontal direction. Polarization control has now become an essential tool to study systems with axial anisotropy such as chiral (e.g. magnetic) or anti antiferromagnetic system. The advent of an ultrafast, variable-polarization source such as FERMI, permits to achieve high time-resolution in the study of magnetization dynamics. The availability of two color experiments and the high energy per pulse at FERMI allows expanding the range of dichroism experiments to include multi photon and non- linear VUV processes. In this work we report the first characterization of the polarization state of a single-pass free electron laser in the VUV spectral range. The experiment was performed at FERMI FEL-1 operated in the 52 - 26 nm spectral range. Three different polarimeter setups, installed at the end of experimental beamlines, were used to characterize the four "pure" polarization states: horizontal, vertical, right-circular and left-circular. The impact of transport optics on the FEL polarization was also assessed. Results from different setups validate each other and allow a cross calibration of the instruments.

9210-23, Session 5

Proposal for a source size and source position monitor for high power x-ray sources based on a "negative" pin-hole camera

Werner H. Jark, Elettra-Sincrotrone Trieste S.C.p.A. (Italy)

Up to now when the refraction of X-rays in material was concerned the interest was always on the refracted beam. The first experiments of Larsson et al [A. Larsson et al, Naturwiss. 12, 1212-1213 (1924)] dealt with the determination of the refractive index of matter. X-rays were found to be refracted appreciably, when they impinged at very grazing angle onto the edge of a flat slice of material. A slice of limited length presents its surface as a projection of finite extend to the incident X-rays. Then a plane wave will be refracted uniformly over the entire height of the projection. The refraction changes the beam crossection and an observer will then register a related refracted beam onto which the absorption depending on the coordinate of the intersection point at the sample is

superimposed (W. Jark et al, Opt. Comm. 284, 4525–4528(2011)]. This "positive" refraction is deflecting the transmitted beam away from the straight-through direction, where one will now find a shadow as the result of "negative" refraction. The incident beam passing outside of the projection of the inclined surface can leak intensity into the shadow only due to edge diffraction at the borders of the projection.

This contribution will discuss with experimental examples, how the source size and the source position can be extracted from the images registered with such "negative" pin-hole camera. Shorter slices (<1 mm) in low absorbing materials (e.g. beryllium or diamond) are feasible for low power absorption at high power sources.

9210-24, Session 5

Intensity interferometry measurement at LCLS

Sanghoon Song, SLAC National Accelerator Lab. (United States)

Intensity interferometry measurements were carried out to study the transverse coherence properties of the SASE LCLS beam in the hard X-ray regime. The parameters to generate the SASE radiation were varied systematically: the electron bunch charge, the reflection order of the crystal analyzer to control the bandwidth of the radiation, and the total undulator length. The statistical analysis of the 2nd order spatial intensity correlation function was based on the ensemble average of a large number of pulses. Preliminary findings are consistent with the expected behavior of that of a thermal source and will be presented.

Conference 9211: Target Diagnostics Physics and Engineering for Inertial Confinement Fusion III

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9211-1, Session 1

Proof of principle test of a novel framing camera for high-energy x-ray imaging *(Invited Paper)*

Nobuhiko Izumi, Gareth N. Hall, Arthur C. Carpenter, Fred V. Allen, Jason G. Cruz, Brian Felker, Joe P. Holder, Kenneth W. Piston, Otto L. Landen, Alexander A. Lumbard, Richard C. Montesanti, Nathan E. Palmer, Richard A. Zacharias, Riccardo Tommasini, David K. Bradley, Perry M. Bell, Joseph D. Kilkenny, Lawrence Livermore National Lab. (United States)

X-ray framing cameras based on proximity-focus microchannel plates (MCP) have been playing an important role as diagnostics of inertial confinement fusion experiments [1]. Most of the current x-ray framing cameras consist of a single MCP, a phosphor, and a recording device (e.g. CCD or photographic films). This configuration is successful for imaging x-rays with energies below 20 keV, but detective quantum efficiency (DQE) above 20 keV is severely reduced due to the large gain differential between top and bottom of plate for these volumetrically absorbed photons [2].Recently developed diagnostic techniques at LLNL require recording backlit images of extremely dense imploded plasmas using hard x-rays, and demand the detector to be sensitive to photons with energies higher than 50 keV.To increase the sensitivity in the high energy region, we propose to use a combination of two MCPs. The first MCP is operated in low gain regime and works as a thick photocathode, and the second MCP works as a high gain electron multiplier. This dual MCP configuration makes it possible to increase the high energy DQE of the camera by an estimated factor of 5-10x. The test results of the proof-of-principle module will be reported.

Prepared by LLNL under Contract DE-AC52-07NA27344.

[1] J. D. Kilkenny, Laser Part. Beams 9, 49 (1991)

[2] J. E. Bateman, et al., Nucl. Instr. and Meth 144, 537 (1977)

9211-2, Session 1

AXIS: an instrument for imaging Compton radiographs using ARC on the NIF

Gareth N. Hall, Nobuhiko Izumi, Riccardo Tommasini, Arthur C. Carpenter, Nathan E. Palmer, Richard A. Zacharias, Brian Felker, Joe P. Holder, Fred V. Allen, Perry M. Bell, David K. Bradley, Richard C. Montesanti, Lawrence Livermore National Lab. (United States)

Compton radiography is an important diagnostic for Inertial Confinement Fusion, as it provides a means to measure the density and asymmetries of an ICF capsule near the time of peak compression. The AXIS instrument (ARC X-ray Imaging System) is a gated detector in development at the National Ignition Facility, and will initially be capable of recording two Compton radiographs during a single NIF shot. AXIS is the detector for Compton radiography driven by the ARC laser, which will be used to produce a Bremsstrahlung X-ray backlighter source over the range of 30keV to 200keV for this purpose. The design of the AXIS diagnostic, its integration into the ARC Compton radiography system, and the expected performance specifications will be discussed.

Prepared by LLNL under Contract DE-AC52-07NA27344

9211-3, Session 1

Electron imaging system for ultrafast diagnostics of HEDLP

Wei Gai, Argonne National Lab. (United States); Jiaqi Qiu, Argonne National Lab. (United States) and Euclid Techlabs, LLC (United States); Chunguang Jing, Argonne National Lab. (United States) and Euclid Techlans, LLC (United States)

A high energy electron beam is proposed to be used for time resolved imaging measurements of high energy density processes in HEDLP. Generation of a high quality sub-picosecond electron beam with present RF photocathode technologies is technologically mature and cost effective. An electron bunch train with a flexible time structure is used to penetrate a time varying high density target. By imaging the scattered electron beam, the detailed target profile and its density evolution can be accurately determined. An imaging lattice design and particle tracking simulation is finished to investigate the general physics and feasibility of this method. Tungsten is used to instead of ICF target in the simulation. One simulation example shows that for areal densities in the range 0.01~1 g/cm2, an electron beam consisting of a train of ~800 MeV bunchlets, each a few ps long and with charges ~nC is suitable. A sharp image with ~1um resolution could be obtained for 200 um tungsten.

9211-4, Session 1

Results of hard x-ray imaging from OMEGA

Daniel A. Lemieux, Los Alamos National Lab. (United States); H. Bradford Barber, The Univ. of Arizona (United States); Gary P. Grim, Los Alamos National Lab. (United States)

No Abstract Available

9211-5, Session 1

Mk x Nk gated CMOS imager

James R. Janesick, SRI International Sarnoff (United States); Perry M. Bell, Alan Teruya, Joseph R. Kimbrough, Lawrence Livermore National Lab. (United States); James Andrews, John Tower, Tom Elliott, SRI International Sarnoff (United States); Jeanne Bishop, Chronicle Technology Inc. (United States)

Our paper will describe a new recently designed large 4k x 4k x 10 um pixel CMOS gated imager intended to be employed at the LLNL National Ignition Facility (NIF). The monolithic imager is based on stitchable 1k x 1k pixel blocks. The Mk x Nk format structure and reticule system can be extended to large format sizes by selecting M and N (i.e., M = 1, 2, . .11 and N = 1, 2, . . 11). For example a 11k x 11k x 10 um pixel CMOS imager can be fabricated. The imager chosen by NIF is stitched onto a 200 mm silicon wafer and yield up to nine 4k x 4k imagers in addition to several 1k smaller imagers used for engineering purposes. Details behind the design are discussed including global reset feature important to fully erase the imager of charge following fusion ignition in approximately 300 ns. Numerous performance data products from several previous fabricated prototype CMOS arrays on which the Mk x Nk design is based will be presented.

9211-6, Session 2

High-rep rate target development for ultra-intense interaction science at the Central Laser Facility *(Invited Paper)*

Nicola Booth, Central Laser Facility (United Kingdom); Daniel Symes, Rutherford Appleton Lab. (United Kingdom); David Neely, Central Laser Facility (United Kingdom); Rajeev P. Pattathil, Martin Tolley, Christopher Spindloe, Rutherford Appleton Lab. (United Kingdom); Stephanie Tomlinson, Central Laser Facility (United Kingdom); Robert Heathcote, Rutherford Appleton Lab. (United Kingdom); Robert J Clarke, Central Laser Facility (United Kingdom); Dean Rusby, University of Strathclyde (United Kingdom)

The requirement from large scale facilities for high repetition rate operations is rapidly approaching, and is increasingly important for studies into high intensity secondary source generation, QED studies and the push for inertial confinement fusion. It is envisioned that multiple PW systems at high repetition rates will be built for projects such as the European Extreme Light Infrastructure project. Depending on the interaction physics involved, a number of differing parameters in the interaction increase in importance, including positioning accuracy and target surface quality, and to ensure reproducible optimum interaction conditions, presents a significant problem for accurate target positioning. With these requirements in mind, a co-ordinated project is underway at the Central Laser Facility amongst the experimental science, engineering and target fabrication groups, to tackle some of the challenges that we as a community face in working towards high repetition rate operations. Here I will present the latest work being undertaken at the CLF to improve capability in key areas of this project, specifically in the areas of reliable motion control and rapid target positioning.

9211-7, Session 2

New results from thulium activation experiments at the National Ignition Facility

Gary P. Grim, Robert S. Rundberg, Anna C. Hayes, Gerard Jungman, Melissa Boswell, Malcolm M. Fowler, Andi Klein, Jerry B. Wilhelmy, Los Alamos National Lab. (United States); A. Tonchev, C. Yeamans, Lawrence Livermore National Lab. (United States)

No Abstract Available

9211-8, Session 2

A fast scintillation telescope system to measure neutron induced beta decay

Andi Klein, Robert S. Rundberg, Malcolm M. Fowler, Gary P. Grim, Melissa Boswell, Jerry B. Wilhelmy, Los Alamos National Lab. (United States)

We will present the results from measurement of neutron activation at the Omega Laser Facilty in Rochester.

The system consists of 4 plastic scintillators in series, are readout through different readout electronics, We will show the achieved energy resolution for the detected beta decays and the advantage of using simultaneous time and energy measurement to discriminate between the different decay channels and activated atoms.

9211-9, Session 2

Engineering architecture of the neutron Time-of-Flight (nToF) diagnostic suite at the National Ignition Facility

Todd J. Clancy, Joseph A. Caggiano, Mark J. Eckart, Mike Moran, James M. McNaney, Stephan Friedrich, Robert Hatarik, Edward Hartouni, James P. Knauer, Lawrence Livermore National Lab. (United States); Vladimir Glebov, Univ. of Rochester (United States)

This paper describes the engineering architecture and function of the neutron Time-of-Flight (nToF) diagnostic suite installed on the NIF at LLNL. These instruments provide key measures of neutron yield, ion temperature, neutron bang-time, and downscatter fraction.

Currently, there are four nToFs on three collimated lines-of-site (LOS) from 18 to 27m from Target Chamber Center, and three positioned 4.5m from TCC, within the NIF Target Chamber but outside the vacuum boundary by use of re-entrant wells on three other LOS.

NIF nToFs measure the time history, and equivalent energy spectrum, of reaction generated neutrons from a NIF experiment. Neutrons are transduced into electrical signals, which are then carried either by coaxial or Mach Zehnder transmission systems that feed splitter assemblies and fiducially timed digitizing oscilloscopes outside the NIF Target Bay shield wall.

One method of transduction employs a two-stage process wherein a neutron is converted to scintillation photons in a hydrocarbon doped plastic (20x40mm) or bibenzyl crystal (280x1050mm), which are subsequently converted to an electrical signal in a photomultiplier tube or a photodiode.

An alternative approach for higher neutron yields uses a single-stage conversion of neutron-to-electron by use of a very thin, 0.25 to 1 mm, Chemical Vapor Deposited Diamond (CVD-D) disc of radius 2 to 24mm under high voltage bias. In comparison to the scintillator method, CVD-Ds have fast rise and decay times (< ns), have very low residual tails, are insensitive to shot gammas, and are less sensitive to the neutron signal of interest.

9211-10, Session 3

Single line-of-sight imaging system for plasma interactions *(Invited Paper)*

Terance J. Hilsabeck, Joseph D. Kilkenny, Tae Chung, Brian S. Sammuli, General Atomics (United States); Perry M. Bell, Joseph R. Kimbrough, Lawrence Livermore National Lab. (United States); Jonathan D. Hares, T. D. Bradshaw, Kentech Instruments Ltd. (United Kingdom)

A multi-frame single line-of-sight ultrafast camera has been developed using the electron pulse-dilation imaging technique. The device employs a photocathode with a swept accelerating potential to slow down the temporal evolution of incoming optical information. A large axial magnetic field is used to maintain focus in the electron image. A multiply gated back-end microchannel plate detector with ns response time separates and records individual frames representing different times with a single image formation at the input. Experimental results and calculations describing performance parameters which may be achieved with instruments constructed using this technique are presented.

Work supported by U.S. Department of Energy under Contract DE-AC52-06NA27279.

9211-11, Session 3

Kirkpatrick Baez Optics fielding and alignment on the National Ignition Facility

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The Kirkpatrick Baez Optics (KBO) diagnostic used on the National Ignition Facility has defined its mirror location repeatability requirements to be within a 150 micron spherical diameter each time that it is extended along its telescoping rail path during offline alignment and during its use on the NIF. When extended, the mirrors are located at the end of a Diagnostic Load Package, cantilevered more than three meters out from its bolted connection points. Discussed are the structural challenges and the mechanical design solutions that were implemented to achieve the 150 micron location repeatability goal of the diagnostic.

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9211-12, Session 3

Improvements to an MCP based high speed x-ray framing camera to have increased robustness in a high neutron environment

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As neutron yields continue to increase on NIF the need for neutron 'hardened' diagnostics has become increasingly important. Gated Imagers, in particular, are very susceptible to neutron induced noise which degrades the image quality and damage to the electronics. We have incorporated numerous upgrades to our Gated Imagers to maintain our image signal to noise ratio and mitigate neutron induced damage. The NIF Gated Xray Detector (GXD) has evolved into the hardened Gated Xray Detector (hGXD). These improvements will be presented as well as image data taken on high yield NIF shots showing the enhanced image quality. Additional upgrades have been added to ease operational use and remotely locate sensitive electronics.

Work supported by U.S. Department of Energy under Contract DE-AC52-06NA27279.

9211-13, Session 4

Mach-Zehnder detector system issues and enhancements for use on the NIF DANTE x-ray diagnostic

Bart Beeman, Lawrence Livermore National Lab. (United States); Kirk Miller, National Security Technologies, LLC (United States); William R. Donaldson, Univ. of Rochester (United States); Arthur C. Carpenter, Joseph R. Kimbrough, Todd J. Clancy, Bob Chow, Essex Bond, Zaylis Zayas-Rivera, Perry M. Bell, John Celeste, Andrew MacPhee, Klaus Widmann, Lawrence Livermore National Lab. (United States); R. Q. Abbott, K. K. Lee, J. C. Peterson, S. M. Gordoni, National Security Technologies, LLC (United States); John J. Buckley, National Security Technology (United States); Anatoly B. Golod, Lawrence Livermore National Lab (United States)

We present lessons learned from the fielding of various Mach-Zehnder based diagnostic systems on the National Ignition Facility (NIF) and potential solutions. The DANTE X-ray diagnostic is the next in a series of applications for Mach-Zehnder based signal transport and acquisition systems on NIF and as such will incorporate many of these upgrades. In addition to extended dynamic-range performance and improved reliability, the upgrades presented also enable multiplexing of the signals from DANTE's 18 X-ray diodes to economize on system cost and rack space. Previous deployments on other NIF diagnostics highlighted the necessity to decouple the input light intensity from the bias point of the Mach-Zehnder. Areas of concern including polarization, temperature, bias point and optical power level control will be addressed.

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9211-14, Session 4

Target material collection for High-Energy Imaging Diagnostic

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The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory uses the world's largest lasers to compress materials to levels found within planets, allowing for experiments in high-energy-density (HED) science. After a NIF shot, the target material breaks up and is ejected at extremely high velocities, up to 10 km/s. For future shots, it is desirable to minimize distribution of the target material within the NIF. The High Energy Imaging Diagnostic (HEIDI), which comes within 8 cm of the target, will be modified to minimize the distribution of the ejected material. An external cone will be added to HEIDI which will block a larger angle than the existing hardware. Internal shielding will be added to isolate target material within the front portion of the diagnostic. A thin aluminum bumper will slow low-density vaporized material, and vaporize high velocity particles, while a thicker wall will collect solid chunks. After the shot, an external cover will be installed, to collect any stray material that might be disturbed by regular operations. The target material will be retrieved from the various shielding mechanisms and assayed.

9211-15, Session 4

Streaked x-ray spectrometer for the National Ignition Facility

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A time-resolved x-ray spectrometer operating in the 2 to 18 keV photon energy range has been designed, constructed and calibrated for the National Ignition Facility (NIF). The NIF X-ray Spectrometer (NXS) uses a tilted, elliptical Bragg-reflection geometry. It operates on the Diagnostic insertion manipulator Imaging Streak Camera (DISC) that has a temporal record lasting 1 to 20 ns and a corresponding temporal resolution of 8 to 160 ps. NXS will be absolutely calibrated on OMEGA using laser-driven, spherically symmetric, mm-scale x-ray sources of K- and L-shell emission from a variety of metals (Mo, Ag, Si, Ti, Cr, Ni, Zn, Zr). The 2 to 18 keV range is divided into ten discrete spectral windows, due to the finite number of spatial resolution elements in DISC. A time-integrated record of the spectrum on an image plate detector provides an in-situ photometric calibration of the streaked spectrum. The spectral range of the Bragg-reflected beam incident on the DISC x-ray photocathode is defined by the ellipticity and 2d-spacing of the singly-curved Bragg crystal and the tilt angle of the ellipse. The Bragg crystals are cleaved from boules of PET, RbAP or KAP crystals. NXS will have a spectral resolving power (E/dE) greater than 50 for mm-scale x-ray sources. An overview of the NXS project will be presented.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This work supported by the Defense Threat Reduction Agency under IAA 10027-5009 – BASIC, “DTRA time-resolved x-ray spectrometer for the National Ignition Facility”. This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC52-08NA28302.

9211-16, Session 4

Performance and operational upgrades of x-ray streak camera photocathode assemblies at NIF

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X-ray streak cameras are used at the National Ignition Facility for time-resolved measurements of many important inertial confinement fusion metrics such as capsule implosion velocity, self-emission burn width, and x-ray bang time (time of brightest x-ray emission). Recently a design effort was undertaken to improve the performance and operation of the streak camera photocathode and related assemblies. The performance improvements include a new optical design for the input of UV timing fiducial pulses that increases collection efficiency of electrons off the photocathode, repeatability and precision of the photocathode pack assembly, and increase the input field of view for upcoming experiments. The operational improvements will provide the ability to replace photocathode packs between experiments in the field without removing the diagnostic from the Diagnostic Instrument Manipulator (DIM). The new design and preliminary results are presented. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. LLNL-ABS-649444

9211-17, Session PMon

Kirkpatrick-Baez microscope with spherical multilayer mirrors around 2.5keV photon energy

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A Kirkpatrick-Baez (KB) x-ray microscope has been developed for the diagnostics of inertial confinement fusion (ICF). The KB microscope system works around 2.5keV with the magnification of 20X. It consists of two spherical multilayer mirrors. The grazing angle is 3.575° for the photon energy needed. The influence of the slope error of optical components and the alignment errors is simulated by SHADOW software. The mechanical structure which can perform fine tuning is designed. Experiment result with Manson x-ray source shows that the spatial resolution of the system is about 3.1-3.7?m over a field of view of 200?m.

9212-40, Session PMon

Powder diffraction-based microtomography for depicting phase distributions in bulk materials

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Hard X-ray microtomography (µCT) is frequently applied in materials research due to its excellent capabilities for depicting the internal morphology of a specimen. Specially by employing synchrotron radiation for µCT, an outstanding sensitivity can be achieved. Recently, the combination of scanning CT schemes with powder diffraction-based information allowed for extending tomographic contrast (XRD-µCT), so as to depict spatial phase distributions on one reconstruction slice. We used the so-called ID22NI beamline (ESRF) to apply XRD-µCT in combination with full-field µCT schemes to selected problems from materials research which have so far not been accessible with µCT alone. Data processing was performed using the XRDUA software.

The presentation highlights developments in terms of the instrumentation as well as scientific results: one of them being mechanically triggered phase transformations like in zirconia-based dental prostheses, induced by clinically practised surface manipulations. They are of high clinical relevance due to their significant influence on the failure behaviour of the latter. All the methods applied so far were essentially surface-probing. By using XRD-µCT it was for the first time possible to visualize and quantify the depth of the transformation layer. A different topic is the potential of heat-treated TiH2 powder for metal foam production: it requires knowledge on the spatial distributions of crystalline phases within the powder particles. XRD-µCT performed using a nano-focused beam reveals that these distributions tend to be very irregular. Hence, the aimed shift of hydrogen release into the melting range of the foaming metal alloy cannot be explained by simple core-shell models.

9212-42, Session PMon

High-resolution x-ray computed tomography to understand ruminant phylogeny

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High-resolution X-ray computed tomography has become a vital technique to study fossils down to the true micrometer level. Paleontological research requires the non-destructive analysis of internal structures of fossil specimens. We show how X-ray computed tomography enables us to visualize the inner ear of extinct and extant ruminants without skull destruction. The inner ear, a sensory organ for hearing and balance has a rather complex three-dimensional morphology and thus provides relevant phylogenetical information what has been to date essentially shown in primates. We made visible the inner ears of a set of living and fossil ruminants using the phoenix|x-ray nanotom® m (General Electric Wunstorf, Germany) equipped with a 180 kV / 15 W transmission X-ray tube with a nanofocus source. Because of the high absorbing objects a tungsten target was used and the experiments were performed with an accelerating voltage of 180 kV and a beam current of 30 ?A. During the scans 1440 equiangular radiographs were taken over 360° with a resulting pixel size of 20 ?m. Possible stem ruminants of the living families are known in the fossil record but extreme morphological convergences in external structures such as teeth is a strong limitation to our understanding of the evolutionary history of this economically important group of animals. We thus investigate the inner ear to assess its phylogenetical potential for ruminants and our first results show strong family-level morphological differences.

9212-43, Session PMon

Integrated high-throughput tomography experiment control environment

Igor Khokhriakov, Felix Beckmann, Lars Lottermoser, Helmholtz-Zentrum Geesthacht (Germany)

The Helmholtz-Zentrum Geesthacht is operating beamlines optimized for materials research using synchrotron radiation at the Deutsches Elektronen-Synchrotron DESY in Hamburg and beamlines using neutrons at the FRM II in Munich. With the beginning of the operation of the 3rd generation synchrotron-radiation source PETRA III, Hamburg, and the design and planning of the new neutron source ESS, Lund, there is a strong demand to increase the data throughput, to make optimal use of the beamtime, together with a full controlled experiment. Especially in tomography the data pipeline from the experiment to the 3D reconstruction has to be redesigned.

Furthermore, the extensive progress in hardware in recent years makes it now possible to develop nearly real time tomography experiment control system. Such system can perform all the routines that are necessary for the experiment and provide real time feedback to the user. This feedback can be used for instant monitoring and/or for real time reconstruction.

The most important task for such system is the collection of the data. The data can be divided into three main groups: 1) static data; 2) data collected during the experiment; 3) persistent data. The system consists of several components that implement tango framework. Tango is a control system widely used in synchrotron community. Nevertheless all the components are implemented in such a way so they can be easily integrated into a different control environment (TINE, EPICS). To gather the static data a dedicated tango server was developed. During the experiment three other tango servers collect the status data. So called StatusServer tango server can access also other control systems (TANGO, TINE, EPICS). Another tango server – ControlServer performs the experiment. Finally the third tango server acquires all data and stores it in the NeXus format. NeXus format is a special data format designed by Helmholtz foundation in order to introduce a common data format for neutron, x-ray and muon science. This data can be interpreted on the fly, for instance to generate a feedback or to perform a reconstruction.

This system is now in an approbation stage at IBL (P05) and HEMS (P07) beamlines, PETRA III, DESY, Hamburg, Germany.

All the components are open source and freely available at http://bitbucket.org/hzgwpn

9212-44, Session PMon

Development and integration of an intelligent detector for grating-based phase-contrast tomography

Pavel Lytaev, Alexander C. Hipp, Lars Lottermoser, Julia Herzen, Imke Greving, Igor Khokhriakov, Stephan Meyer-Loges, Joern Plewka, Jörg Burmester, Helmholtz-Zentrum Geesthacht (Germany); Michele Caselle, Matthias Vogelgesang, Suren Chilingaryan, Andreas Kopmann, Matthias Balzer, Karlsruher Institut für Technologie (Germany); Felix Beckmann, Martin Müller, Andreas Schreyer, Helmholtz-Zentrum Geesthacht (Germany)

The Helmholtz-Zentrum Geesthacht (HZG) is operating microtomography

stations using synchrotron radiation at the high brilliance third-generation synchrotron light source PETRA III at Deutsches Elektronen-Synchrotron (DESY) in Hamburg. The stations are optimized for different photon energies and are installed at the Imaging Beam Line (IBL, P05) and High Energy Material Science (HEMS, P07). Absorption contrast and phase contrast techniques were developed and applied to samples in the fields of medicine, biology, and materials science.

The present work is devoted to the development of an intelligent detector with high-speed data acquisition for experiments using grating based differential phase-contrast (DPC) imaging. The detector is based on the ultrafast streaming camera platform (UFO-project) developed at the Karlsruhe Institute of Technology (KIT) [http://www.ufo.kit.edu]. The detector setup will be optimized for the microtomography setups at our stations.

In this work we present the current status of the project. We have tested several camera systems. For each setup we measured the photon transfer curve, which indicates statistical parameters such as read out noise, conversion gain and full well capacity. These characteristics are required to optimize the operation of the detector according to the processing speed and signal quality in the course of the phase-contrast imaging process.

At the HEMS beamline we aligned the DPC imaging setup at 45 keV. We performed DPC projection measurements using different parameters. We varied the number of phase steps, the number of periods and the exposure time for two different camera systems:

a) Commercial 14 bit CCD camera, SC09000M-NS-LCDD, KAF09000 monochrome, Digital Imaging System, 3056x3056 array size, 12 um pixel size.

b) UFO-project 12 bit camera, CMOS Image Sensor, CMV2000-2E5M1PP monochrome, 2048x1088 array size, 5.5 um pixel size.

The experimental results will be compared and used to optimize the detector operation.

The project is a part of the Helmholtz Detector Platform [http:www.helmholtz-detectors.de].

9212-45, Session PMon

Image Reconstruction for X-ray K-edge Imaging with a Photon Counting Detector

Bo Meng, Wenxiang Cong, Yan Xi, Ge Wang, Rensselaer Polytechnic Institute (United States)

Objective: In the image space, a linear attenuation coefficient can be represented as a linear combination of the linear attenuation coefficients of component materials weighted by their respective concentrations. When incoming x-rays are spectrally filtered, projection data in different energy windows can be measured, and used to reconstruct multiple linear attenuation coefficient images. Given these reconstructed linear attenuation coefficients and the expected values of the component materials, it is feasible to decompose an object into constituent materials quantitatively. In this paper, we demonstrate that three types of materials can be effectively separated using an X-ray source coupled with three spectral filters. An essential step is to choose the type and thickness of the spectral filter so that contrast-to-noise (CNR) and signal- to- noise (SNR) are balanced. Methods: We will perform a numerical simulation study with respect to different types and thicknesses of filters for an x-ray source operated at 140kVp. The 20cm diameter water-filled cylindrical phantom is used which consists of five smaller cylinders of different diameters filled with water and different contrast materials respectively, which can be represented in terms of three base materials. The reconstructed concentrations are in good agreement with the true concentrations. The accuracy and precision are analyzed in a clinical CT imaging setting.

9212-46, Session PMon

Portable uCT as a diagnostic tool for cultural heritage materials: a case study from the Huaca del Sol (Trujillo, Peru) adobe

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High permeability through the matter and non-destructive probe radiation makes X-ray photons a for studies in applied sciences. In particular X-ray computed tomography (CT), is a non-destructive analytical tool to investigate the inner structure of a solid material with high spatial resolution.

High resolution X-ray tomography is currently obtained at synchrotron radiation (SR) facilities. Compared to SR, conventional X-ray tubes deliver a beam whose flux is very low, not energetically homogeneous and incoherent, but they are free-access and low cost sources. However, a rapid development of the X-ray optics devices makes X-ray conventional tubes a powerful diagnostic and analytical experimental setup in several fields.

Complementary with micro-tomography, X-ray fluorescence analysis (XRF) allows a non-destructive qualitative and quantitative elemental characterization. With the exception of SR, which is a suitable probe for microspots, it is often challenging to perform table-top ?-XRF analysis. Polycapillary lenses designed for X-ray beam focusing now offer alternative laboratory solutions for ?-XRF 2D and 3D mapping [1-3]. The combination of polycapillary optics and a fine-focus X-ray tube (with a source-spot diameter less than 50 ?m) can thus provide high-intensity radiation fluxes necessary for elemental analysis. Compared with a pinhole or a monocapillary [4], an optimized “X-ray source-optics system” can result in a radiation density gain of more than 3 orders of magnitude.

In this work, we relate on the first study aimed at reconstructing the porosity and microchemical composition of a fragment of ancient adobe sampled at the archeological site of the Huaca del Sol (Peru) through 3D ?-Tomography and ?-XRF 2D mapping using a tabletop experimental layout based on polycapillary optics. We finally compare our data with SR results.

9212-47, Session PMon

Carotid plaque characterization using CT and MRI imaging acquisition and synergistic image analysis

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Noninvasive determination of plaque vulnerability has been a holy grail for many years. Despite advances in imaging, there is currently no effective way to identify vulnerable atherosclerotic plaques. Computed tomography (CT) and magnetic resonance imaging (MRI) are used, but neither provides sufficient information for reliable determination of plaque stability. Thus, we combined CT and MRI imaging to determine if the composite information can better reflect the histological determination of plaque vulnerability. Two human endarterectomy specimens (1 symptomatic carotid and 1 stable femoral) were imaged using Scanco Medical Viva CT40 and Bruker Pharmascan 16cm 7T Horizontal MRI

/ MRS systems. ?CT scans were done at 55 kVp and tube current of 70 mA. Samples underwent RARE-VTR and MSME pulse sequences to measure T1, T2 values, and proton density. The specimens were processed for histology and scored for vulnerability using the American Heart Association criteria. Single and multiple modality-based analyses were performed through segmentation of key imaging biomarkers (i.e. calcification and lumen), image registration, measurement of fibrous capsule, and multi-component T1 and T2 decay modeling. Joint CT-MRI image analysis was compared with that of the individual modalities and histology. Feature differences were analyzed between the unstable and stable controls, symptomatic carotid and femoral plaque, respectively. It has been shown that CT-MRI is a promising tool to improve vulnerable plaque characterization.

9212-48, Session PMon

CT image-based quantification of sub-pixel diameter micro-particle accumulations in tissues using a priori biological information

Andrew J. Vercnocke, Jill L. Anderson, Steven M. Jorgensen, Erik L. Ritman, Mayo Clinic College of Medicine (United States)

This study explores the ability to count and/or accurately estimate the size of x-ray opaque microscopic particles that cast an x-ray shadow which is smaller than a detector pixel of a CT scanning system (i.e., sub-resolution). Although nano-CT now makes imaging of even nanometer diameter particles possible this method does not allow convenient imaging of volumes of the order of 1 cm? or larger (e.g., intact mouse organs or large animal tissue biopsies) and would involve very high radiation exposures. In this study we show that a priori knowledge of the particle clustering behavior can be used to make a more accurate estimate of particle number. The a priori knowledge used is based on the power-law character of clustering behavior of those particles within tissue. The utility of this concept is examined using CT scan data with 10, 20, 30 and 40 µm on-a-side detector pixels imaging 25 µm diameter microspheres (impregnated with gold or silver) embolized in the coronary microcirculation of pigs.

9212-49, Session PMon

TV minimization-based multimodal medical image reconstruction

Xuelin N. Cui, Virginia Tech (United States); Hengyong Yu, Wake Forest Univ. School of Medicine (United States); Ge Wang, Rensselaer Polytechnic Institute (United States)

Since its recent introduction, simultaneous image reconstruction for multimodality fusion has been an interesting topic for superior imaging performance. Also, the compressive sensing (CS) based image reconstruction methods are widely investigated because they can potentially reduce the amount of raw data significantly. In this work, we use CS as a crucial component to combine computed tomography (CT) and magnetic resonance imaging (MRI) into a single reconstruction framework. Theoretically speaking, the CS-based reconstruction methods require prior sparsity knowledge of an object to be reconstructed. In addition to the conventional L2 norm of the data fidelity term, the multimodal image information is also intended to improve the reconstructed image quality via cross correlation. The prior information in this context is that most of the medical images can be modeled as piecewise constant functions, and the discrete gradient transform (DGT) can serve as a sparse representation, whose L1 norm is the total variation (TV). More importantly, the multimodal images from the same object should share some structural similarity that can be captured by DGT as well. The prior information on similar distributions from the sparse DGTs is employed to improve the CT and MRI image quality synergistically for a CT-MRI scanner platform. Numerical simulation with under-sampled CT and MRI datasets is conducted to demonstrate the merits of the proposed hybrid image reconstruction approach. Our preliminary results confirm that the proposed hybrid reconstruction method outperforms the conventional CT and MRI reconstructions when they are performed separately.

9212-50, Session PMon

High-resolution in-situ modular lab-scale x-ray computed tomography (XCT) system for 4D materials science

James Mertens, Jason Williams, Nik Chawla, Arizona State Univ. (United States)

A lab-scale, cone-beam x-ray computed tomography system was constructed from modular components to facilitate in-house, three dimensional, high-resolution imaging for the non-destructive in situ quantification of microstructure evolution under an external stimulus. The system compliments data acquired via synchrotron XCT in terms of accessibility, availability, flexibility, and radiation energy. Performance-critical components include a dual-target microfocus x-ray source, a sample rotation stage, a scintillating screen, and a large-format optical CCD camera. Implementation of a dual-target x-ray tube enables sample-specific data optimization by selectively compromising between the resolution loss in high-flux configurations preferred for heavily attenuating samples, and the transmissivity challenges experienced in high-resolution configurations. A custom x-ray detector was incorporated in the system that is optimized for a given sample in the trade-off between spatial resolution and detection efficiency.

System design, data acquisition, and data processing methods will be discussed which address challenges in lab-scale computed tomography, particularly for systems deployed for the study of material microstructure and evolution phenomena. Issues addressed include weak feature signal and contrast, high-energy x-ray noise, detector system defects, x-ray beam instability, and beam-hardening. All of these factors can have severe ramifications on sample reconstruction quality. Design and data handling approaches for minimizing these effects will be described, with examples of relevant material systems and microstructures which provide challenges in computed tomography.

9212-51, Session PMon

ANKAphase: Software for single-distance phase-retrieval from inline x-ray phase contrast radiographs

Alexander Rack, ESRF - The European Synchrotron (France); David Haas, Karlsruher Institut für Technologie (Germany); Timm Weitkamp, Synchrotron SOLEIL (France)

In our poster we will present a computer program named ANKAphase that implements a single-distance phase retrieval algorithm by D. Paganin. The program is designed to process stacks of images, on which it can additionally perform flatfield normalization and subtraction of dark images. It is thus adapted for the pre-processing of tomography data sets (although it does not perform tomography reconstruction itself). An intuitive graphical user interface makes it accessible to non-experts. It is written in Java and runs on most of the common computer platforms and operating system. It can be used as a standalone application or as a plugin to the widely-used open-source image viewing/processing program ImageJ.

9212-52, Session PMon

High-performance data management and analysis for tomography

Dilworth Y. Parkinson, Alastair A. MacDowell, Lawrence Berkeley National Lab. (United States)

The Advanced Light Source (ALS) is a third-generation synchrotron X-ray source. It operates as a user facility with nearly 40 beamlines and hosts over 2000 users per year from around the world. Users of the Hard X-ray Micro-Tomography Beamline (8.3.2) often collect more than 1 Terabyte of data per day, generating multiple additional Terabytes of processed data. The data rate continues to increase rapidly due to faster detectors and new sample automation capabilities. We will present the development and deployment of a computational pipeline, termed "SPOT", fed by data from the ALS, and powered by the storage, networking, and computing resources of the National Energy Research Scientific Computing Center (NERSC) and the Energy Sciences Network (ESnet). After one year of operation, SPOT contains 70,000 datasets and 350 TB of data from 85 users. All datasets collected at the Hard X-ray Tomography Beamline are automatically reconstructed using both parameters set by users in the data acquisition control system, and those that are automatically detected. Results are presented to users for visualization through a secure web portal. Users can then download their data or launch a (currently limited but growing) number of operations based on the data—such as filtering, segmentation, and simulation. The massive computational resources of NERSC are thus made available on a level that is easily accessible to the full range of micro-tomography users.

9212-53, Session PMon

In situ fatigue analysis of micro gaps in dental implants

Wolfram Wiest, Simon A. Zabler, Christian Fella, Andreas Balles, Julius-Maximilians-Univ. Würzburg (Germany); Alexander Rack, ESRF - The European Synchrotron (France); Katja Nelson, Univ. Medical Ctr. Freiburg (Germany); Randolf Hanke, Julius-Maximilians-Univ. Würzburg (Germany)

Dental implants are frequently used in the modern maxillofacial surgery. These titanium implants are complicated to model in terms of fatigue, because they consist of two components. Concerning mechanical bending strength the connection of these two parts, the implant-abutment connection, appears to be the weakest link [1].

To measure microgaps at the implant-abutment connection in situ it is necessary to use partially coherent X-ray sources as well as image post-processing. The edge enhancement of the inline phase contrast imaging yields excellent detectability of the microgaps which are further quantified in width through comparison with forward optical wave- simulations. With this method it is possible to measure even microgaps which are much smaller than the detector resolution [2]. Recently tomography study on fatigued samples was conducted after the fatigue treatment [3].

In this presentation, we will show the experimental setup for real in situ tomography during fatigue testing of dental titanium implants. Because of the short exposure time during a fatigue process of 10Hz, the phase contrast micro-CT measurements had to take place at the synchrotron (ID 19, ESRF, France). To shorten the fatigue time, the common routine was applied under stepwise increasing cyclic load.

[1] S. Zabler et al. (2012). Int. J. Mat. Res. 103 - 2, 207-216.

[2] S. Zabler et al. (2010). Rev. Sci. Instrum. 81, 103703.

[3] P. Bleuet et al. (2004) Proc. Of SPIE 5535

9212-1,

Trends in the micro- and nano-CT: 2012-2014

Stuart R. Stock, Northwestern Univ. (United States)

Trends in the type and distribution of published micro- and nano-CT studies are reviewed in this paper. The literature of the last two years is covered, i.e., the period between Developments in X-ray Tomography VIII (2012) and the present.

9212-2, Session 1

Grating interferometry-based phase microtomography of atherosclerotic human arteries *(Invited Paper)*

Marzia Buscema, Margaret N. Holme, Georg Schulz, Peter Thalmann, Basel Univ. Hospital (Switzerland); Simone E. Hieber, Univ. Basel (Switzerland) and Basel Univ. Hospital (Switzerland); Vartan Kurtcuoglu, Univ. of Zürich (Switzerland); Magdalena Müller-Gerbl, Univ. Basel (Switzerland); Till Saxer, Hôpitaux Univ. de Genève (Switzerland); Felix Beckmann, Julia Herzen, Helmholtz-Zentrum Geesthacht (Germany); Bert Müller, Basel Univ. Hospital (Switzerland)

The simultaneous visualization of soft and hard tissues using hard X-ray-based computed tomography is challenging as the X-ray absorption strongly depends on the atomic number and tissue density. In such situations, phase contrast methods like grating interferometry have significant advantages, as the phase shift is only a linear function of the atomic number. We performed grating interferometry-based phase tomography in stepping mode (five steps over one period of the interferometer fringe pattern) at HASYLAB, DESY, Hamburg, Germany with the experimental setup of the Helmholtz Research Center. Here we show that this is a powerful method for obtaining three-dimensional visualizations of a variety of anatomical features in atherosclerotic human coronary arteries, which include plaque, muscle, fat, and connective tissue. After dissection, three coronary arteries with a diameter of about 6 mm were fixed in 4 % formalin before tomographic data acquisition in a water bath using a photon energy of 33 keV and 2.4 ?m effective pixel size. The tomography data were processed to reconstruct the vessel lumen morphology of the diseased arteries. Computational grids were derived from the voxel-based lumina to perform fluid dynamics simulations and to determine the wall shear stress in the plaque-induced constrictions of the human arteries. Wall shear stress was at least an order of magnitude higher in critical stenosis (greater than 80% constriction by cross sectional area) than in healthy blood vessels. The wall shear stress data are the main input for optimizing the release threshold of mechano-sensitive nano-containers for the local treatment of atherosclerosis.

9212-3, Session 1

Single grating phase contrast imaging for x-ray microscopy and microtomography

Peter Bruyndonckx, Alexander Sasov, Bart Pauwels, Bruker microCT (Belgium)

Grating-based phase contrast and dark field x-ray imaging has been proven as a successful technique when using polychromatic sources. A disadvantage of this Talbot-Laue approach is the inefficient use of the dose due to the presence of two absorption gratings. The thick absorption gratings also limit the FOV due to clipping effects. In addition, the phase stepping procedure requires that at least 4 images need to be taking at each projection angle to extract the differential phase and dark field information.

To sidestep these issues, we performed a compact proof-of-principle experiment using a cone-beam geometry set-up with a single phase grating (Pi/2 phase shift at 8 keV, 2.69 micron period) and a high resolution x-ray detector. The phase grating pitch and set-up geometry were chosen such that one period of the Talbot pattern was covered by exactly four detector pixels, allowing to implement a virtual analyzer grating and perform the phase stepping procedure in software using a single exposure. Having only one grating in the set-up also makes the alignment easier and reduces phase drifts due to grating movements. Since a virtual absorption grating is perfectly absorbing it resulted in an enhanced visibility of 45% to 55%.

A projection x-ray image of a Nylon wire confirmed that the index of

refraction computed from the extracted differential phase image was within 5% of the tabulated value.

9212-4, Session 1

Quantitative edge illumination x-ray phase contrast tomography

Charlotte K. Hagen, Paul C. Diemoz, Marco Endrizzi, Univ. College London (United Kingdom); Luigi Rigon, Fulvia Arfelli, Istituto Nazionale di Fisica Nucleare (Italy); Diego Dreoosi, Sincrotrone Trieste S.C.p.A. (Italy); Frances C. Lopez, Renata Longo, Istituto Nazionale di Fisica Nucleare (Italy); Alessandro Olivo, Univ. College London (United Kingdom)

X-ray phase contrast imaging (XPCi) methods are sensitive to phase in addition to attenuation effects and can achieve improved image contrast for weakly absorbing materials, such as often encountered in biomedical applications. Several XPCi methods exist, most of which have already been implemented in computed tomographic (CT) modality, thus allowing volumetric imaging. Among the existing techniques, the Edge Illumination (EI) XPCi method has high potential for widespread application, as it is based on a simple working principle, can be implemented both at synchrotrons and in laboratories, scaled up to large fields of view and is robust with respect to environmental vibrations. Moreover, high phase sensitivity and dose efficiency have been demonstrated, which makes it a promising tool for biomedical studies. Despite these advantages, EI XPCi had, until now, not been implemented in CT mode.

We will briefly introduce the theory for the extension of the method from planar imaging to CT. The reconstruction of quantitative 3D maps of an object's phase and attenuation will be discussed; moreover, we will present a theory for the reconstruction of combined 3D phase and attenuation maps. Both reconstruction strategies find applications in multimodal tissue characterisation and the identification of faint, weakly absorbing details. Experimental results, obtained with both synchrotron and laboratory-based sources, for a custom-built phantom and a biological sample, will be shown, which validate the theory and confirm the superiority of the phase over conventional, absorption-based image contrast.

Our results, which were achieved at low entrance doses, indicate the suitability of EI XPCi for tomographic phase contrast imaging of biological samples. The method has a high potential to become a useful tool for biomedical imaging in the future, for example for the study of small animals.

9212-5, Session 1

X-ray phase-contrast imaging at PETRA III

Alexander C. Hipp, Julia Herzen, Pavel Lytaev, Felix Beckmann, Imke Greving, Fabian Wilde, Malte Ogurreck, Thomas Dose, Lars Lottermoser, Rene Kirchhof, Igor Khokhriakov, Hilmar Burmester, Martin Müller, Andreas Schreyer, Helmholtz-Zentrum Geesthacht (Germany)

Conventional absorption-based imaging often lacks in good contrast for special applications like visualisation of soft tissue or weakly absorbing material in general.

To overcome this limitation, several new X-ray phase-contrast imaging methods have been developed at synchrotron radiation facilities. Our aim is to establish the possibility of different phase-contrast imaging modalities at the Imaging Beamline (IBL, P05) and the High Energy Material Science Beamline (HEMS, P07) at PETRA III.

In this paper we will give an overview of the currently implemented phase-contrast modalities, which are optimised to the different given conditions at the two beamlines.

We installed a grating interferometer (consisting of two gratings) with a fixed geometry usable at a large variety of energies at the HEMS beamline without need of mechanical changes. We will present first results of a high energy phantom sample obtained at different energies in the range from 33 up to 100 keV. Also first results on biomedical samples will be presented. By reference to those we will demonstrate the advantage of using a high-energy setup to avoid artefacts in the tomographic reconstruction usually occurring from phase-wrapping or too high absorbing samples.

Our investigations at the P05 beamline focus on propagation-based phase-contrast imaging and the single-shot approach using a single-grating interferometer. First results will be presented showing an experimental comparison of those two modalities in terms of sensitivity and image quality.

9212-6, Session 2

Dictionary learning-based low-dose x-ray CT reconstruction *(Invited Paper)*

Xuanqin Mou, Junfeng Wu, Ti Bai, Qiong Xu, Xi'an Jiaotong Univ. (China); Hengyong Yu, Wake Forest Univ. School of Medicine (United States); Ge Wang, Rensselaer Polytechnic Institute (United States)

Since X-ray radiation is potentially harmful to human, the radiation dose involved in medical x-ray CT scanning has received increasingly more public attention. Hence, a hot topic is how to reduce x-ray dose as much as possible while maintaining the image quality. The low-dose strategies include reduction in x-ray tube current and minimization of dataset size. However, these will result in insufficient and noisy projection data, which represent a great challenge to image reconstruction. We have been working to combine statistical iterative methods and advanced image processing techniques, especially dictionary learning, and produced excellent feasibility results. In this paper, we will present recent progress in dictionary learning based low-dose CT reconstruction and discuss the selection of regularization parameters that are crucial in the algorithmic optimization. The key idea is to use a balance principle based on a model function to choose the regularization parameters during the iterative process, and to determine a weight factor empirically for balance with respect to the noise level in the projection domain. Numerical and experimental results will be reported to demonstrate the merits of our proposed reconstruction approach.

9212-7, Session 2

Practical pseudo-3D registration for large tomographic images

Xuan Liu, Alexander Sasov, Kjell Laperre, Bruker microCT (Belgium)

Image registration is a powerful tool in various tomographic applications. Our main focus is for microCT applications in which samples/animals can be scanned multiple times under different conditions or at different time points. For this purpose, a registration tool capable of handling fairly large volumes has been developed, using pseudo-3D method to achieve fast and interactive registration with simultaneous 3D visualization.

To reduce computation complexity in 3D registration, we decompose it into several 2D registrations, which are applied to the orthogonal views (transaxial, sagittal and coronal) sequentially and iteratively. After registration in each view, the next view is retrieved with the new transformation matrix for registration. This reduces the computation complexity significantly. For rigid transform, we only need to search for 3 parameters (2 shifts, 1 rotation) instead of 6 (3 shifts, 3 rotations). In addition, the amount of pixels involved is also significantly reduced.

Rigid transform is used for registration, which is intensity-based using sum of square pixel-difference as similarity measure. The searching engine is Powell's conjugate direction method. We have noticed that more information can be used in the 2D registration if one uses maximum-intensity-projections or parallel projections instead of the orthogonal views. Also, other similarity measures, such as mutual information, can be easily incorporated.

Our initial evaluation on microCT data shows very promising results. Application examples include trabecular structure modifications obtained from in-vivo scanning of mice in different time points, structural changes in materials during compression tests, etc.

This method can be extended by adding scaling to the transform model. Further evaluation on registration accuracy between pseudo-3D method and 3D method will be conducted.

9212-8, Session 2

Strategies for efficient scanning and reconstruction methods on very large objects with high-energy x-ray computed tomography

Nils Reims, Tobias Schön, Michael Böhnel, Michael Salamon, Frank Sukowski, Markus Firsching, Fraunhofer-Institut für Integrierte Schaltungen (IIS) (Germany)

X-ray computed tomography (CT) is an established tool for industrial non-destructive testing purposes. Yet conventional CT devices pose limitations regarding specimen dimensions and material thicknesses. Here we introduce a novel CT system capable of inspecting very large objects (VLO) like automobiles or sea freight containers in 3-D and discuss strategies for efficient scanning and reconstruction methods.

The system utilizes a 9 MeV linear accelerator to achieve high penetration lengths in both dense and high-Z materials. The line detector array has an overall length of 4 meters. The presented system allows for reconstruction volumes of 3.2 meters in diameter and 5 meters in height.

First we outline the general capabilities of high energy CT imaging and compare it with state of the art 450 kV X-ray systems. The imaging performance is shown based on experimental results. The second part addresses the problem of considerably higher scanning times when using line detectors compared to planar detectors. Reducing the number of projections considerably causes image artifacts with standard reconstruction methods like filtered back projection (FBP). Alternative techniques which can provide significantly better results are algebraic methods. One of these is compressed sensing (CS) which we discuss regarding its suitability in respect to FBP.

We could prove the feasibility of inspecting VLOs like complete cars or sea freight containers based on experimental datasets. CS allows for achieving sufficient image quality in terms of spatial and contrast resolution while reducing the number of projections significantly resulting in faster scanning times.

9212-9, Session 2

X-ray beam-hardening correction by varying the input spectrum

Jeremy Holt, Mahsa Paziresh, Andrew M. Kingston, Adrian P. Sheppard, The Australian National Univ. (Australia)

In computed tomography (CT) the objective function is X-ray attenuation which varies with material and X-ray energy. The spectrum of lab-based micro-focus X-ray sources are polychromatic and give rise to beam-hardening artifacts in micro-CT since low-energy (or soft) X-rays are attenuated preferentially to hard X-rays. The spectrum can be tuned by setting the accelerating voltage and modifying the material and/or the thickness of the beam filter. Over-filtering results in a more ``monochromatic” beam but sacrifices X-ray flux, and thus signal-to-noise-ratio (SNR). Imaging at low energies is better for material discrimination and has greater Brehmsstrahlung X-ray flux, however, suffers more from beam-hardening artifacts.

It is therefore advantageous to be able to perform CT with low-energy X-rays and correct for beam-hardening post-acquisition. A common software technique is to use a linearisation curve that corrects the deviation from pure Beer-Lambert attenuation. This paper presents several techniques to determine the correction curve parameter values by using additional high-energy input data in the form of a radiograph or a low-resolution scan.

A ``monochromatic” radiograph taken at the same orientation as any radiograph of the CT acquisition with more filtering and potentially a different tube voltage can directly provide a linearisation curve through the 2D histogram between the two radiographs. A higher-energy low-resolution scan gives a tomogram with no beam-hardening but with reduced material discrimination. The coefficients of a linearisation curve can be determined as those that minimise entropy in the 2D histogram of the low-resolution high- and low-energy spectrum tomograms.

9212-10, Session 2

Improving spatial-resolution in high cone-angle micro-CT by source deblurring

Heyang Li, Andrew M. Kingston, Glenn R. Myers, Benoit Recur, Michael L. Turner, Andrian P. Sheppard, The Australian National Univ. (Australia)

Nano scale computed tomography (CT) can resolve many features in cellular structures, bone formations, minerals properties and composite materials not seen at lower spatial-resolution. Those features enable us to build a more comprehensive model for the object of interest. CT resolution is limited by a fundamental trade off between source size and signal-to-noise ratio (SNR) for a given acquisition time. There is a limit on the X-ray flux that can be emitted from a certain source size, and fewer photons cause a lower SNR. A large source size creates penumbral blurring in the radiograph, limiting the effective spatial-resolution in the reconstruction.

High cone-angle CT improves SNR by increasing the X-ray solid angle that passes through the sample. In the high cone-angle regime current source deblurring methods break down due to incomplete modelling of the physical process. This paper presents high cone-angle source de-blurring models. We implement these models using a novel multi-slice Richardson-Lucy (M-RL) and 3D Conjugate Gradient deconvolution on experimental high cone-angle data to improve the spatial-resolution of the reconstructed volume. In M-RL, we slice the back projection volume into subsets which can be considered to have a relative uniform convolution kernel. We compare these results to those obtained from standard reconstruction techniques and current source deblurring methods (i.e. 2D and 3D Richardson-Lucy in the radiograph and the volume respectively).

9212-11, Session 3

Diffraction computed tomography reveals the inner structure of complex biominerals *(Invited Paper)*

Hanna Leemreize, Mie Birkbak, Aarhus Univ. (Denmark); Simon Frølich, Aarhus University (Denmark); Peter Kenesei, Jonathan D Almer, X-ray Science Division, Argonne National Laboratory (United States); Stuart R. Stock, Northwestern Univ. (United States); Henrik Birkedal, Aarhus Univ. (Denmark)

Biological materials are outstanding example of complex hierarchical 3D multicomponent materials for which the advanced structure dictates the desired function. Their characterization is very challenging because of their multifaceted structures. Tomographic techniques are particularly useful in this regard as they allow determining 3D structural characteristics of the materials. Many biological materials are biomineralized and present several mineral phases. Often these cannot be distinguished by standard tomographic techniques. However, basing tomographic reconstructions on the X-ray diffraction signal rather than the absorption signal allows mapping distributions of different crystalline phases. The use of diffraction tomography will be discussed

in connection with investigations of the complex mineralized attachment organ of a mussel, a model for how to make advanced underwater adhesive systems [1]. Detailed analysis of diffraction information allows determining chemical substitution effects in the biomineral lattices and also yields even more advanced microstructural information. Diffraction tomography thus bridges the atomic and tomographic length scales.

[1] H. Leemreize, J. D. Almer, S. R. Stock, H. Birkedal J. Roy. Soc. Interface (2013), 10, 20130319, DOI 10-1098/rsif.2013.0319

9212-12, Session 3

Synchrotron-based characterization of interconnections in microelectronics: recent 3D results

Pierre Bleuet, Guillaume Audoit, CEA-LETI (France); Julien Bertheau, STMicroelectronics (France); Jean Charbonnier, CEA-LETI (France); Peter Cloetens, European Synchrotron Radiation Facility (France); Larissa Djomeni, Dario Ferreira Sanchez, CEA-LETI (France); Fiqiri Hodaj, Science et Ingénierie des Matériaux et Procédés (France); Patrice Gergaud, CEA-LETI (France); Frederic Lorut, STMicroelectronics (France); Jean-Sébastien Micha, CEA-INAC (France); Aurélie Thuaire, Univ. Grenoble Alpes, F-38000 (France) and CEA, LETI, MINATEC Campus (France); Olivier Ulrich, CEA-INAC (France)

The physical characterization of 3D interconnections like TSV and copper pillar is receiving increasing attention because of reliability issues such as voiding, cracking and performance degradation. Those components have a 3D architecture with features in the deep sub-micrometer range. For that purpose, the use of synchrotron radiation to perform a multimodal characterization is of interest.

Here, we show the potential of synchrotron-based hard x-ray nanotomography to investigate the morphology of TSV and copper pillars, using both projection (holotomography) and scanning (fluorescence) 3D imaging, based on a series of experiments performed at the ESRF. In particular, we highlight the benefit of the method to characterize voids, but also the distribution of intermetallics in copper pillars, which plays a critical role for the device reliability.

Beyond morphological imaging, an original acquisition scheme based on scanning Laue tomography is introduced. It consists in performing a raster scan (z,?) of a sample illuminated by a white x-ray beam while recording diffraction data. After processing and image reconstruction, it allows for 3D reconstruction of grain orientation, strain and stress in copper TSV and also in the surrounding Si matrix.

[1] Bertheau et al., ECTC, 2013.

[2] Martin et al., Rev. Sci. Instr. (2013).

This work was supported by LETI & ST Microelectronics fundings, the French “Recherche Technologie de Base” program, the CATRENE project MASTER3D and the ANR AMOS program. Experiments were performed at the ESRF beamlines ID22NI and BM32 based on samples fabricated and prepared at the PFNC, at LETI.

9212-13, Session 3

Dynamic x-ray tomography imaging application for the study of granular materials

Yujie Wang, Shanghai Jiao Tong Univ. (China); Xianghui Xiao, Kamel Fezzaa, Argonne National Lab. (United States)

It’s important to understand both static and dynamic properties of a granular system which is an important soft matter system. Studying granular systems with x-ray imaging technology, including x-ray computed tomography (CT) and ultrafast x-ray projection imaging, has great superiority. Due to the penetrating properties of x-ray, internal structures of a granular system could be obtained. Using x-ray CT technology, we studied packing problems with various granular systems, such as mono-dispersed hard spheres, wet spheres, rods, poly-dispersed foams, etc. At the same time, ultrafast x-ray phase contrast imaging technology based on synchrotron radiation provides a projective realization of evolving systems, which is one of the few experimental methods that can probe dynamic properties of granular systems. These experimental works will contribute to revealing some important properties of granular systems. We also suggest that with the rapid development of x-ray tomography technique especially with the high-spatial and temporal resolutions, it shows great promises for the study of other soft matter systems including foam, emulsion, and colloids whose study have been previously dominated by scattering techniques.

[1]. Y. Fu, Y. Xi, Y.X. Cao, and Y. Wang, “X-ray microtomography study of compaction process of rods under tapping”, Phys. Rev. E 85, 051311 (2012).

[2]. Y. Cao, B. Chakraborty, G.C. Barker, A. Mehta, and Y. Wang, “Bridges in three-dimensional granular packings: experiments and simulations”, Europhys. Let. 102, 24004 (2013).

[2]. C. Xia, K. Zhu, Y. Cao, H. Sun, B. Kou, and Y.J. Wang, “X-ray tomography study of the random packing structure of ellipsoids”, Soft matter DOI:10.1039/C3sm52841C (2014).

9212-14, Session 3

Investigating the plastic zone at the tip of a crack: A 3D diffraction and imaging study using synchrotron x-rays

Jason Williams, Sudhanshu Singh, Arizona State Univ. (United States); Xianghui Xiao, Francesco De Carlo, Jonathan Almer, Peter Kenesei, Argonne National Lab. (United States); Nik Chawla, Arizona State Univ. (United States)

Advances in experimental methods, analytical techniques, and computational approaches, have enabled the development of three dimensional (3D) analyses. The study of 3D microstructures under an external stimulus (e.g., stress, temperature, environment) is particularly exciting. Synchrotron generated x-rays provide a wonderful means of characterizing damage in materials non-destructively.

In this talk, we will describe experiments that attempt to quantify the size, distribution, and origin of the plastic zone at the tip of a crack in an aluminum alloy. Many theoretical analyses have been made to describe this plastic zone. In this work, we have combined 3D x-ray tomography and 3D diffraction tomography to obtain a full-scale, 3D characterization of the plastic zone at the tip of the crack. The experiments were conducted in situ, using a sophisticated loading jig, in a 7075 aluminum alloy. The approach involved capturing the microstructure by in situ deformation in an x-ray synchrotron, followed by x-ray tomography and image analysis, as well as diffraction tomography analysis. Quantitative comparisons to theoretical estimates of the plastic zone, for a given stress and crack length, were conducted and will be discussed.

9212-15, Session 3

Fast imaging and tomography applications at Advanced Photon Source (APS)

Xianghui Xiao, Doga Gürsoy, Francesco De Carlo, Argonne National Lab. (United States)

The non-destructive nature of x-ray imaging makes it invaluable not only in medical applications but also multidiscipline researches. With the high photon flux from synchrotron sources, x-ray imaging with such sources provides not only high spatial resolution but also high temporal resolution that is suitable in dynamical phenomena studies, in biology, geoscience, and material science/engineering.

In the past few years fast SR-CT has seen significant development

at many different synchrotron facilities all around of world. While temporal resolution is important in time resolving SR-CT, spatial resolution, sensitivity, and other specific factors are also concerned in different application in different degree. In this talk we will present few fast tomography applications at APS and discuss how specific scan parameters were determined in the example cases.

9212-16, Session 4

Molecular imaging with a MARS spectral scanner *(Invited Paper)*

Anthony P. H. Butler, Univ. of Otago, Christchurch (New Zealand) and CERN (New Zealand) and MARS Bioimaging Ltd. (New Zealand); Nigel Anderson, Univ. of Otago, Christchurch (New Zealand); Steven Gieseg, Univ. of Otago, Christchurch (New Zealand) and Univ. of Canterbury (New Zealand); Tim Woodfield, Univ. of Otago, Christchurch (New Zealand); Stephen T. Bell, MARS Bioimaging Ltd. (New Zealand); Philip H. Butler, CERN (New Zealand) and MARS Bioimaging Ltd. (New Zealand) and Univ. of Canterbury (New Zealand)

Molecular imaging is now possible using energy resolved computed tomography scanners. One pre-clinical example of this is the MARS scanner. This spectral scanner operates in the 30-140keV range and has a rotating gantry to allow imaging of live small animals and wet specimens. The detector is a Medipix3RX ASIC bonded to either CZT, CdTe, or GaAs. This detector has a pixel pitch of 110um but retains excellent energy resolution because of inter-pixel communication that ensures charge is collected over an area of greater than 220um. Image recovery is performed using an algebraic reconstruction technique coupled to one of several material discrimination methods.

To date pre-clinical imaging has focused on atheroma characterization and joint health. Atheroma imaging enables characterization of intrinsic plaque components such as fat, water, and calcium. In addition, using targeted gold nano-particles it is possible to identify clinically relevant cell types within regions of the atheroma. For joint imaging, using a spectral scanner it is possible to remove artifacts such as beam hardening that traditionally limit the use of CT around metallic implants. Assessment of cartilage health appears to be possible using using iodine based contrast agents that correlate to glycos-aminoglycan concentrations within the cartilage.

9212-17, Session 4

Brute force absorption contrast microtomography *(Invited Paper)*

Graham R. Davis, David Mills, Queen Mary, Univ. of London (United Kingdom)

The ability to resolve features in X-ray tomography depends not only on spatial resolution, but also on the relative X-ray interactions. Conventional tomography relies on differences in X-ray absorption. An alternative is phase contrast tomography, which relies on differences in refractive index. Where absorption contrast is low, feature resolution can also be achieved by simply increasing the number of X-ray photons, thus reducing the statistical noise. In most laboratory microtomography systems, this statistical noise is the dominant noise source, but as the X-ray exposure is increased, other sources become more significant and in extreme cases dominate. Ring artefacts are caused by differences in sensitivity in adjacent detector elements and may be reduced by moving either the detector or specimen between projections. This movement prevents the errors from summing to form rings, but does not eliminate them as a source of image variability. Flat field correction alone is not a perfect solution since the detector responses may differ in linearity. Time-delay integration (TDI) readout eliminates these differences in sensitivity but in the basic linear form, where the camera is translated through the X-ray shadow during readout, no compensation is made for irregularities in the X-ray field, such as occurs with defects, debris or sputtered target material on the X-ray window. Angular TDI eliminates these irregularities as well as the need for taking a white-field image. Here we present examples of high contrast tomographic reconstructions and also single projections at extreme contrast using TDI systems.

9212-18, Session 4

Liquid-metal-jet x-ray tube technology and tomography applications

Emil Espes, Christina Gratorp, Oscar Hemberg, Göran Johansson, Johan Kronstedt, Mikael Otendal, Björn Sundman, Per A. Takman, Tomi T. Tuohimaa, Excillum AB (Sweden)

The power and brightness of electron-impact microfocus X-ray tubes have long been limited by thermal damage in the anode. This limit is overcome by the liquid-metal-jet anode (MetalJet) technology that has previously demonstrated [1] brightness in the range of one order of magnitude above current state-of-the art sources. This is possible due to the regenerative nature of this anode and the fact that the anode is already molten, which allows for significantly higher e-beam power density than on conventional solid anodes.

Over the last years, the MetalJet technology has developed from prototypes into fully operational and stable X-ray tubes running in many labs over the world. Key applications include X-ray diffraction and scattering, but recently several publications [2,3,4,5] have also shown very impressive X-ray computed tomography results using the liquid-metal-jet anode technology, especially in phase contrast imaging.

This presentation will review the current status of the technology specifically in terms of stability, lifetime, flux and brightness, with a clear focus on its applicability for X-ray computed tomography. It will also discuss details of the liquid-metal-jet technology with a focus on the fundamental limitations of the technology. It will furthermore refer to some recent data from applications within X-ray computed tomography.

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[2] D. H. Larsson; U. Lundström; U. Westermark; P. A. C. Takman; A. Burvall; M. Arsenian Henriksson; H. M. Hertz, Small-animal tomography with a liquid-metal-jet x-ray source, SPIE Proceedings Vol. 8313 Medical Imaging 2012: Physics of Medical Imaging

[3] Simon Zabler; Thomas Ebensperger; Christian Fella; Randolf Hanke, High-resolution X-ray imaging for lab-based materials research, Conference on Industrial Computed Tomography, Wels, Austria 2012

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[5] Matthias Bartels; Victor H. Hernandez; Martin Krenkel; Tobias Moser; Tim Salditt, Phase contrast tomography of the mouse cochlea at microfocus x-ray sources, Applied Physics Letters 103, 083703 (2013)

9212-19, Session 4

An evaluation to design high-performance pinhole array detector module for four head SPECT: a simulation study

Tasneem Rahman, Murat Tahtali, Mark R. Pickering, UNSW@ ADFA (Australia)

The purpose of this study is to derive optimized parameters for a detector module employing an of-the-shelf X-ray camera and a lenslet style pinhole array collimator applicable for a range of different SPECT systems. Monte Carlo simulations using the Geant4 application for tomographic emission (GATE) were performed to estimate the performance of the pinhole array collimators and were compared to that of low energy high resolution (LEHR) parallel-hole collimator in a four head SPECT system. A detector module was simulated to have 50

mm by 50 mm active area along with 50?m holes at 0.48 mm pitch on a tungsten plate. Perpendicular lead septa were employed to acquire non-overlapping projections and to improve reconstructed image quality. Different diameters of water and rod phantoms were used to evaluate the performance of the proposed four head SPECT system of the pinhole array detector module. SPECT images were reconstructed where activity distribution was well visualized, and 10 to 4 mm diameter rods could be resolved in the reconstructed images. 100 by 100 pinhole configuration in each head is expected to demonstrate better sensitivity and detection efficiency for 140 keV ?-rays compared to LEHR parallel hole collimator. In this study we have designed a pinhole array imaging system providing good resolution and system sensitivity over a large FOV along with high detection efficiency comparing to the conventional four head SPECT system. The proposed detector module is expected to provide improved performance in various SPECT imaging.

9212-20, Session 4

NanoXCT: development of a laboratory nano-CT system

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The NanoXCT EU FP7 project [1] aims at developing a laboratory, i.e. bench top sized nano-CT system with a large field-of-view (FOV) for non-destructive testing needs in the micro- and nano-technology sector. The targeted voxel size is 50 nm at 0.175 mm FOV, the maximum FOV is 1 mm at 285 nm voxel size. Within the project a suitable X-ray source, detector and manipulation system are being developed. To cover the demand for elemental analysis, the system also includes X-ray fluorescence tomography.

The system concept omits the use of X-ray optics, to be able to provide a large FOV of up to 1 mm and to preserve the flexibility of state-of-the-art micro-CT systems. The targeted resolution will be reached via direct geometric magnification made possible by the development of a specialized high-flux nano-focus transmission X-ray tube.

Timepix [2] Hexa modules were chosen as the basis for the detector system, since a photon counting detector is advantageous for the long exposure times that come with very small focal spot sizes. Other reasons include the small pixel size and adjustable energy threshold.

In this contribution we introduce the system concept including design goals and constraints, and the individual components. We present the current state of the prototype development including first results.

[1] http://www.nanoxct.eu/

[2] Llopart, X., et al., NIM A 581.1 (2007): 485-494, http://dx.doi.org/10.1016/j.nima.2007.08.079

9212-21, Session 5

High-energy attenuation-contrast and phase-contrast microtomography using synchrotron radiation at DESY *(Invited Paper)*

Felix Beckmann, Helmholtz-Zentrum Geesthacht (Germany)

The Helmholtz-Zentrum Geesthacht is operating the user experiments for microtomography using synchrotron radiation at Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany. In the recent years attenuation-contrast and phase-contrast techniques were developed and applied as user experiments at the beamline W2 / DORIS which was specialized for materials-science applications using high energy X-rays. Due to the shutdown of the storage ring DORIS, which cover the large field of view microtomgraphy systems, the new microtomography station at the P07 / PETRA has to be extended to include all high-energy microtomography applications. Therefore, scanning tomography has to be applied as an user experiment for attenuation contrast and phase contrast. For different applications optimized detector systems can be included. In the talk an overview of the microtomography stations at PETRA will be given. The new software pipeline for high throughput tomography and the status of the ongoing detector development will be presented and demonstrated for selected measurements.

9212-22, Session 5

TomoPy: A framework for the analysis of synchrotron tomographic data

Doga Gürsoy, Francesco De Carlo, Xianghui Xiao, Argonne National Lab. (United States); Chris Jacobsen, Argonne National Laboratory (United States)

Analysis of large tomographic datasets at synchrotron light sources is becoming progressively more challenging due to the increasing data acquisition rates that new technologies in X-ray sources and detectors enable. The next generation of synchrotron facilities that are currently under design or construction throughout the world will provide diffraction limited X-ray sources and is expected to boost the current data rates by several orders of magnitude and stress the need for the development and integration of efficient analysis tools more than ever. Here we describe in detail a collaborative framework for the analysis of synchrotron tomographic data that has the potential to unify the effort of different facilities and beamlines performing similar tasks. The proposed Python/C++ based framework is open-source, OS and data format independent, parallelizable and supports functional programming that many researchers prefer. This collaborative platform has the potential to affect all major synchrotron facilities where considerable effort is now dedicated into developing new numerical methods to be deployed at the facility for real time processing as well as distributed to users for off site data processing

9212-23, Session 5

P05: Imaging beamline at PETRA III

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The imaging beamline (P05) operated by Helmholtz Zentrum Geesthacht (HZG) at the DESY PETRA III storage ring consists of two experimental stations [1]: A micro- and a nano-tomography end station. The high photon flux provided by PETRA III is well suited for imaging applications achieving high density and spatial resolutions. Furthermore, the high coherence at PETRA III is well suited for phase contrast imaging techniques. Main fields of application for P05 are materials science (e.g. quantitative analysis of pores, cracks, alloying processes), biology and geology (e.g. plants, insects, sediments) and medicine (e.g. implant materials, structures of bones, tissues, and teeth).

The micro tomography setup at P05 is very versatile and designed to allow the easy implementation of both user-supplied and in-house sample environments.

We will present an overview of the experimental setup as well as the available in-house sample environments (oven, corrosion cell). In addition some examples of the wide range of applications using the micro tomography station at P05 will be shown.

Furthermore, we present first results of the nano-tomography end station.

These were obtained with an X-ray microscopy setup, which operates in an energy range of 15 to 30 keV using polymer compound refractive lenses (CRLs) and rolled prism lenses developed at the KIT [2,3]. With this full field microscopy setup we achieved a resolution better than 200 nm line and space over a field of view of 50 µm x 50 µm.

References:

[1] A. Haibel et al., Powder Diff 25, 161 (2010)

[2] F. Marschall et al., Journal of Physics: Conference Series, accepted (2014)

[3] H. Vogt et al., Proc. SPIE 8076, 80760I, doi:10.1117/12.890037 (2011)

9212-24, Session 5

X-ray imaging at ESRF including future upgrade *(Invited Paper)*

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The current and future ESRF X-ray imaging beamlines offer unique instruments for studying complex systems from the microscale to the nanoscale. Each beamline developed a specific focus in terms of application fields and corresponding observed variables, experimental techniques and energy range. These capabilities are currently strongly enhanced by the ESRF Upgrade Programme. Phase I (ongoing) aims to enable scientists using the ESRF to access a new generation of beamlines while Phase II (future) focuses on a major upgrade of the ESRF storage ring. A (r)evolution reaching towards new frontiers in X-ray imaging is anticipated.

9212-25, Session 6

Tumors in murine brains studied by grating-based phase contrast microtomography *(Invited Paper)*

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Besides the diagnosis of tumors, medical treatment, which includes a combination of surgery, chemical, pharmacological, and radiation therapies, is well established in the present-day fight against cancer. Nevertheless, basic research is indispensible for the development of more powerful approaches to prevent, diagnose and treat cancer diseases. The aim of the present study is the investigation of murine tumors at early (10 days), intermediate (15 days) and late (23 days) stage of growth. Using grating-based phase contrast data acquired at the beamline W2 (HASYLAB, DESY, Hamburg, Germany), operated by Helmholtz Research Center, we demonstrate that this technique yields premium contrast between healthy and cancerous parts of murine brain tissues with a pixel size of 4.7 ?m an a spatial resolution of 8.9 ?m. Using a three gratings interferometer, the experiments were performed at an X-ray energy of 23 keV. Projection radiographs were taken in 801 steps over 360°. At each projection angle, eight phase-stepping images were taken over two periods of the interference pattern. For the experiment C57BL/6J-Tyr< c-2J> or C57BL/6 Albino mice, eight weeks old, weighting 24-26 g (Charles River Laboratories, France) have been used. The mice were injected with a suspension of 10^5 GL261 tumor cells (murine glioma) implanted directly into the right frontal lobe using a stereotactic frame for head fixation. One mouse without injected tumor cells was used as control. The comparison of a control mouse with the three stages enabled us to determine the tumor size and to analyse its internal microstructure.

9212-26, Session 6

X-ray phase contrast tomography from whole organ down to single cells

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We use propagation based hard x-ray phase contrast tomography to explore the three dimensional structure of soft biological tissues from the organ down to sub-cellular level, based on combinations of synchrotron radiation and laboratory sources. To this end, a laboratory based microfocus tomography setup has been built in which the geometry was optimized for phase contrast imaging and tomography [Bartels et. al., APL 103, 083703 (2013)]. By utilizing phase retrieval algorithms, quantitative reconstructions can be obtained that enable automatic renderings without edge artifacts. A high brilliance liquid metal microfocus x-ray source in combination with a high resolution detector can yield resolutions down to 1 µm.

To extend the method to nanoscale resolutions we use a divergent x-ray waveguide beam geometry at the synchrotron. Thus, the magnification can be easily tuned by placing the sample at different defocus distances. Due to the small Fresnel numbers in this geometry the measured images are of holographic nature which poses a challenge in phase retrieval. With down to mono modal x-ray beams resolutions below 30 nm have been achieved. We demonstrate this technique on soft hydrated mouse lung tissue yielding 3D reconstructions for a large field of view and region of interest zoom tomography [Krenkel et. al., in preparation]. To further improve the imaging scheme, we develop new reconstruction algorithms that impose minimal restrictions to the objects, based on an optimized two distance measurement [Krenkel et. al., Opt. Express 21, 2220 (2013)] or on the use of an overlap constraint of different tomographic projections [Ruhlandt et. al., PRA, submitted (2014)].

9212-27, Session 6

Phase microtomography of human brain tissue visualizes the microanatomy of hippocampal sclerosis

Simone E. Hieber, Univ. of Basel (Switzerland); Christopher Kelly, Univ. Hospital Basel (Switzerland); Peter Thalmann, Univ. Basel (Switzerland); Luigi Mariani, Univ. Hospital Basel (Switzerland); Georg Schulz, Univ. Basel (Switzerland); Imke Greving, Helmholtz-Zentrum Geesthacht (Germany); Bert Müller, Univ. Basel (Switzerland)

The visualization of the human brain's microanatomy is one of the challenges in medical imaging. Although magnetic resonance imaging provides deep insights, the spatial resolution is insufficient to study the structure on the level of individual cells. The current knowledge on the brain's microanatomy relies on two-dimensional optical and electron microscopy techniques, which generally require demanding preparation procedures including sectioning and staining. A promising alternative is hard X-ray phase micro-tomography. Within this context, we acquired grating based interferometry tomography datasets of a cylinder 6 mm in diameter from a human hippocampus. The hippocampus was surgically resected from a patient with hippocampal sclerosis. This study was one of the first successful phase tomography measurements at the beam line P05 (HASYLAB at DESY, Hamburg, Germany). The experiments were performed at an X-ray energy of 15 keV with an effective pixel size of 2.4 ?m. The number of projections was 499 over 360° with 5 phase-steps over one period of the interference pattern at each angle. In contrast to sophisticated absorption micro-tomography using nanotom® m (General Electric, Wunstorf, Germany), which failed to show the brain tissue, phase micro-tomography reveals the internal structure.

9212-28, Session 6

Iterative method for x-ray in-line phase-contrast imaging

Wenxiang Cong, Ge Wang, Rensselaer Polytechnic Institute (United States)

In this paper, we present a second-order approximation model with respect to phase shift based on the paraxial Fresnel-Kirchhoff diffraction theory. In the in-line phase-contrast imaging, the phase contrast is formed through the free-space propagation of the beam, which transforms phase variations in the object plane into intensity variations in the image plane. This proposed model accurately establishes a quantitative correspondence between the phases and the recorded intensity images, outperforming the linear phase approximation model used by current popular methods of x-ray in-line phase contrast imaging, which have to assume slow phase variations and weak attenuation of the object. This new model can be solved using Algebraic Reconstruction Technique (ART). The state of the art compressive sensing (CS) techniques can be also incorporated to achieve high quality image reconstruction. Our numerical simulation experiments are performed to demonstrate the feasibility of the proposed approach, which show that the proposed iterative method is more accuracy and stability, and robust against measurement noise comparing with conventional analytic methods.

9212-29, Session 6

X-ray tomography of the guinea pig cochlea to assess damages after noise exposure *(Invited Paper)*

Claus-Peter Richter, Hunter K. Young, Amanda Vo, Whitney Liddy, Stuart R. Stock, Northwestern Univ. (United States); Xianghui Xiao, Argonne National Lab. (United States); Donna Whitlon, Northwestern Univ. (United States)

Longterm (weeks) exposure to sound levels above 90 dB SPL, or short-term exposure to sound levels above 115 dB SPL (hours) will likely result in permanent cochlear damage. At present, no therapy is approved by the Food and Drug Administration (FDA), which protects the ear from those damages, or reverses them. Drug studies are on the way. They can be significantly accelerated by a novel imaging method, computed-tomography of cochlear structures using coherent hard x-rays. Micro-computed tomography was carried out at the 2-BM beamline at the Advanced Photon Source at Argonne National Laboratory. Some of the specimens from this drug study were imaged at the Advanced Photon Source at Argonne. We demonstrate that the method can image soft tissue structures in an intact guinea pig cochlea at a sufficient resolution to detect changes in cochlear soft tissue structures. A counting algorhythm was developed that allowed the assessment of the auditory neurons with the computer within minutes, a task that would take weeks using classical histology. In some cases osmium tetroxide was used to enhance the image contrast and myelinated nerve fiber bundles could be identified. The samples were scanned either while immersed in fluids, which allows further histological processing if required. The result verify that a novel drug, NU12-2, preserves cochlear structures during noise exposure (4 hours at 120 dB SPL).

9212-30, Session 7

Submicrometer structure of sea urchin tooth via remote synchrotron microCT imaging *(Invited Paper)*

Stuart R. Stock, Northwestern Univ. (United States); Alexander Rack, ESRF - The European Synchrotron (France)

Remote electron microscopy sessions are featured at a number of imaging centers. Similarly, many synchrotron light sources offer routine "mail-in" crystallography and powder diffractometry. At imaging beam lines, small numbers of (preliminary) scans are sometimes performed by staff, in the absence of the investigator, to demonstrate feasibility of the proposed study or as an industrial service. In the 1990s, one of us (SRS) participated in processing experiments where samples were couriered between Georgia Tech and SSRL and synchrotron microCT followed the spatial distribution of densification. The authors report results of remote microCT experiments, i.e., where the investigator who knows the sample interacts via the web with the beam line scientist operating the apparatus and provides real-time feedback on where to scan based upon radiographs and on the most recent reconstructions. Local tomography imaged sea urchin teeth with 350 nm isotropic volume element (voxel) at beam line ID-19, ESRF. Sea urchin teeth form by growing parallel plates of high Mg calcite, each of which is 2-5 µm away from its neighbors, and very high Mg calcite columns later link the plates. The remote imaging session focused on tooth positions where the columns were just forming, and column shapes and dimensions were measured, something which has previously only been done with destructive sample preparation and scanning electron microscopy. The experiments were successful despite a separation of 4,400 miles and seven time zones, and the authors have suggestions for making this a more widely used option.

9212-31, Session 7

Characterization of natural and artificial carious lesions and their remineralization using self-assembled peptides

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In a dental office, every day X rays of teeth within the oral cavity are obtained. Caries induces a mineral loss and, therefore, becomes visible by reduced X-ray absorption. In the early stage cases, the regeneration of affected tissue can be accelerated applying short, self-assembled peptides assumed to form supra-molecular networks and trigger the nucleation of hydroxyapatite crystallites within the lesion. The detailed spatial distribution of the mineral loss, however, is inaccessible, since the dose for such studies is intolerable. As a consequence, these measurements can only be performed after tooth extraction. We have taken advantage of synchrotron radiation-based micro computed tomography to characterize a human tooth with a rather small, natural caries lesion and an artificially induced lesion provoked by acidic etching. Both halves of the tooth were separately visualized from 2400 radiographs recorded at the beam line P07 (HASYLAB at DESY, Hamburg, Germany) with an asymmetric rotation axis at photon energy of 45 keV. Because of the setup, one finds an energy shift in the horizontal plane to be corrected. These measurements serve for the calibration of micro computed tomography data of the same tooth from the better accessible phoenix nanotom® m of General Electric, Wunstorf, Germany. Furthermore, the detailed comparison between natural and artificial lesion within the same tooth enables us to judge how far the man-made etching procedure corresponds to the naturally occurred caries process. Such a comparison is essential for reliable tests of remineralization strategies, as the artificial lesions can be prepared in reproducible manner for the optimization purposes. It has been demonstrated that the application of a self-assembled peptide (P11-4) enhances the enamel regeneration by the incorporation of calcium ions into the tooth microstructure.

9212-32, Session 7

Applied x-ray computed tomography with sub-micron resolution in paleontology using laboratory and synchrotron sources

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X-ray computed tomography (CT) is commonly used for imaging samples in biomedical or materials science research. Due to the possibility to obtain high resolution and to visualize a sample in a non-destructive way, X-ray CT is perfectly suited to inspect old fossilized specimens which are mostly unique or rare. The basis of this paleontological research is to investigate Precambrian animals in order to solve several key issues related to their origin and life evolution. This article presents the effectivity of the computed tomography applied on the enigmatic fossil Corumbella werneri, one of the oldest known skeletonized animals originally discovered in Corumbá (Brazil). The perspicacity such as the limits of various tomographic setups are presented: a laboratory-based conventional ?CT setup, a synchrotron source using conventional absorption, a third generation synchrotron source operated in propagation based phase contrast and a novel X-ray ?CT setup with lens-coupled detector system, dedicated for radiography and tomography.

The crucial issues to be investigated concern the morphology and the ultrastructure of the fossil that can highlight the reproduction and life style the fossil had. Therefore, the following specific samples among the rare collected have been subjected to 3D tomography imaging: a well preserved carapace of the fossil, diverse specimens called “eggs” susceptible to be attributed to Corumbella werneri, since they were gathered close to the fossil morphological remains and considering that some Cnidarians of the same class Scyphozoa have a sexual reproduction.

9212-33, Session 7

3D visualization of casts from murine livers and kidneys

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Malfunction of oxygen regulation in kidney and liver may lead to the pathogenesis of chronic diseases. The underlying mechanisms are poorly understood. In kidney, it is hypothesized that renal gas shunting from arteries to veins eliminates excess oxygen. Such shunting is highly dependent on the structure of the renal vascular network. The vascular tree has so far not been quantified under maintenance of its connectivity. Three-dimensional imaging of the vessel tree down to the smallest capillaries, which in mouse model are smaller than 5 ?m in diameter, is a challenging task. An established protocol is to use corrosion casts and apply synchrotron radiation-based micro computed tomography (SR?CT), which provides the desired spatial resolution with the necessary contrast. However, SR?CT is expensive and beamtime access is limited. We show here that measurements with a phoenix nanotom® m (General Electric, Wunstorf, Germany) using a molybdenum target at acceleration voltages between 60 – 90 kV, beam currents between 80 – 90 ?A, pixel sizes of about 1.5 ?m and 1440 projections leads to results comparable to those obtained with SR?CT at beam lines BW2 and P05 (HASYLAB at DESY, Hamburg, Germany) with asymmetric rotation axis with 1440 – 1800 projections, at photon energies between 8 -10 keV and with an effective pixel sizes of 1.15 - 4.3 ?m. The validation of our results is achieved by measurements of two murine kidneys (one is osmium stained) and a liver (osmium stained).

9212-34, Session 7

SEM-based system for 100nm x-ray tomography for the analysis of porous silicon and 3D interconnects

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Synchrotron radiation is a good candidate for 3D imaging at high resolution. However, the difficult access can be prohibitive for daily analyses and we present hereafter a step towards x-ray nanotomography using a laboratory system. In x-ray imaging, the spatial resolution is driven by the x-ray source size. To have a lens-free system, we use an SEM as an electron gun which produces x-rays when interacting with an anode [1]. Such an interaction creates a source size that can be properly shaped using different anode materials and geometries. This flexible system makes it possible to perform x-ray imaging at energies of up to 10keV and resolution down to 100nm. Because of a low SNR, the exposure time is long and forces to have a low angular sampling. This is counterbalanced by using advanced reconstruction algorithms [2].

The technique has been applied to the study of FIB-prepared macroporous silicon samples. Controlled porosification of 200mm silicon wafer has been performed, with thicknesses from few nm to few hundreds of micrometers. We quantified the 3D pore network, which is of interest for the optimization of the production of such materials. Beyond this application, 3D integration (TSV, copper pillar) is also discussed.

[1] Laloum et al., Micron, in press.

[2] Batenburg et al., IEEE Trans. Im. Proc. (2011).

This work was supported by a LETI-FEI common lab, ST Microelectronics fundings, the French “Recherche Technologie de Base” program and the CATRENE project MASTER3D. Experiments were performed at the PFNC at LETI.

9212-35, Session 7

Apocalypto - revealing lost text with XMT

David Mills, Graham R. Davis, Queen Mary, Univ. of London (United Kingdom); Paul L. Rosin, Yukun Lai, Cardiff Univ. (United Kingdom)

We report on the outcome of a long-term, multidisciplinary, international project to recover textual content from degraded rolls and small books using high contrast, high dynamic range XMT developed at QMUL.

In archives, museum and private collections around the world, there exist paper and parchment objects too damaged to produce for inspection and research. Often, any record of their content is lost, or at best incomplete.

Many of the objects, exhibit compound damage from fire and water as well as entropic decay and fungal blooms. The only way to make their textual content available is by imaging. For objects that can be handled and flattened sufficiently, there are conventional optical means of imaging; we are applying XMT to some of the rest that use x-ray contrast inks.

We present methodology and results from several objects suffering water, fungal and fire damage, that we’ve scanned and produced text from. As text retrieval algorithms improve, we can revisit the scan data and produce higher quality text.

9212-36, Session 8

Improving dynamic tomography, through maximum a posteriori estimation

Glenn R. Myers, The Australian National Univ. (Australia); Matthew Geleta, The Univ. of Melbourne (Australia); Andrew M. Kingston, Benoit Recur, Adrian P. Sheppard, The Australian National Univ. (Australia)

The physics of fluid flow in micro-porous materials is dictated by pore-scale fluid displacements. Direct study of this and other dynamic (i.e. time-dependent) processes is not possible with conventional X-ray micro computed tomography (uCT): artifact-free uCT requires a static sample. A compromise is commonly made by periodically halting the process to enable uCT imaging. However, this may alter the process and de-value the experiment.

We have previously verified that a priori knowledge of the underlying physics can be used to conduct true high-resolution, time-resolved 4D imaging of continuous, complex dynamic processes such as pore-scale fluid displacement, at existing X-ray uCT facilities. In this paper we present a maximum a posteriori (MAP) model of the dynamic tomography problem, and show that: (i) our previous dynamic uCT algorithm is a limiting case of this new model; and (ii) the MAP framework improves 4D image quality by allowing us to easily adapt and generalise our dynamic uCT approach to systems with more complex underlying physics, e.g. by explicitly accounting for the importance of rapid, localised advances of one fluid (i.e. Haines jumps). These conclusions are supported with experimental data collected at the ANU lab-based uCT facility.

9212-37, Session 8

Multiresolution tomography using an accurate forward model

Doga Gürsoy, Francesco De Carlo, Xianghui Xiao, Argonne National Lab. (United States)

Merging information from tomography datasets obtained at different resolutions with several orders of magnitude difference, is gaining more and more interest in many applications at synchrotron X-ray imaging facilities. A satisfactory solution to combine micro and nano tomography datasets in an efficient and robust way is still in its infancy. Here we describe a method to improve the image quality for multi-resolution datasets using less computational resources than the Fourier patching based methods which are usually not practical for situations where the resolution ratio is larger than an order of magnitude due to the linear increase in computational resources that such methods pose. The method we propose is based on an accurate registration of the imaging geometry and, utilizing a forward model to estimate the effect of global features of the sample on local regions, iterative correction of residual errors. We will present the performance analysis of this approach for different resolution ratios and the effects of registration and modeling accuracies in the final reconstructions.

9212-38, Session 8

Dual-energy iterative reconstruction for material characterisation

Benoit Recur, Mahsa Paziresh, Glenn R. Myers, Andrew M. Kingston, Shane J. Latham, Adrian P. Sheppard, The Australian National Univ. (Australia)

In the field of material characterisation, dual-energy tomography recovers the distribution of density (rho) and atomic number (Z) of a specimen by combining two energy acquisitions at E1 and E2. Such a characterisation is based on a model of the attenuation (at each point x of the acquired sample) depending on both rho and Z according to the energies used for the acquisition. Usually, these algorithms estimate Z(x) and rho(x) volumes or Zn.rho(x) and rho(x) volumes from the two standard reconstructed attenuation volumes, mu(x,E1) and mu(x,E2). Here we propose a dual-energy expectation maximisation algorithm for transmission tomography (Dual EM-TR), using an attenuation function depending on material characteristics in the forward projection. This reconstruction algorithm recovers rho(x) and Z(x) directly. We compare the results with those obtained through mu(x,E1) and mu(x,E2).

During reconstruction, we estimate the specimen physical characteristics by matching Z and rho at each voxel, x, with a material dictionary. This estimation is based on a probabilistic classification allowing us to allocate the voxel to the most likely material in the dictionary. Partial volume approximations encountered at the interfaces between several materials can be informed by simultaneously computing data segmentation coupled with classification. The classification is verified during subsequent iterations of the dual EM-TR algorithm, allowing false matchings to be corrected. The algorithm results in a reconstruction segmented according to the physical properties of the scanned specimen.

9212-39, Session 8

Iterative reconstruction optimisations for high cone-angle helical micro-CT

Benoit Recur, Andrew M. Kingston, Glenn R. Myers, Adrian P. Sheppard, The Australian National Univ. (Australia)

The micro-CT facility developed at ANU is a high cone-angle helical-scanning system. The high cone-angle is achieved through a large 2D flat-panel detector (400x300 mm, 2048x1536 pixels) positioned 300 mm from the X-ray source. To image specimens at 1 micron resolution requires they be positioned 1.5 mm from the source, resulting in an average magnification of 200x. However, magnification varies by a factor of 5 across the specimen. Here we address several iterative reconstruction challenges encountered with such a setup. These are generally known in medical and industrial cone-beam scanners but can be neglected in these systems. For our large datasets, minimising the number of operations (or iterations) is crucial.

Large cone-angles enables a large pitch to be used, introducing two challenges: (i) non-uniform resolution throughout the reconstruction, (ii) overscan significantly increases reconstructed volume size. (i) can be addressed by using a double-helix and both problems can be improved by using a lower pitch helix (but slows down iterations). This may be overcome using less projections per revolution but leads to more iterations required. Here we investigate the effect of the trajectory, number of projections per revolution, and pitch on memory and reconstruction time required in order to optimise our system.

We also explore techniques to incorporate additional corrections into an iterative reconstruction algorithm. These corrections include compensation for component misalignments/movements during scanning and beam-hardening correction. We investigate the efficiency of a simultaneous correction/reconstruction compared to a work-flow composed of sequential pre-processing/post-processing corrections made from acquired radiographs or reconstructed data.

9213-1, Session 1

High Energy Resolution Transparent Ceramic Garnet Scintillators *(Invited Paper)*

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Breakthrough energy resolution, R(662keV) <4%, has been achieved with an oxide scintillator, Cerium-doped Gadolinium Yttrium Gallium Aluminum Garnet, or GYGAG(Ce), by optimizing fabrication conditions. We find that ceramic GYGAG(Ce) of a given stoichiometric chemical composition can exhibit very different scintillation properties, depending on sintering conditions and post-anneal treatments. Oxide scintillators tend to exhibit multiple scintillation decay components, including some very slow components, classified as "afterglow," and related to shallow traps, thought to be predominantly due to oxygen vacancies. Among the characteristics of transparent ceramic garnet scintillators that can be controlled by fabrication conditions are: scintillation decay component amplitudes, intensity and duration of afterglow, thermoluminescence glow curve peak positions and amplitudes, integrated light yield, light yield non-proportionality, as measured in the Scintillator Light Yield Non-Proportionality Characterization Instrument (SLYNCI), and energy resolution for gamma spectroscopy. We find that the lack of shallow traps provides the fastest decay, very low afterglow, high light yield, but poor light yield proportionality and degraded energy resolution. A moderate population of shallow traps leads to improved energy resolution. A model describing the effect of the "beneficial" traps on the performance of garnet scintillators is being used to deterministically optimize scintillator performance. Methods for characterization of trap distribution and population can provide the basis for quality control in the manufacture of GYGAG(Ce). Transparent ceramic Cerium-doped Gadolinium Garnet, GYGAG(Ce), has a peak emission wavelength of 550 nm that is better matched to Silicon photodetectors than to standard PMTs. We have therefore designed a spectrometer based on pixelated GYGAG(Ce) on a Silicon photodiode array that can provide R(662 keV) =3.5%. In comparison, with large 1-2 in3 size GYGAG(Ce) ceramics we obtain R(662 keV) =4.6% with PMT readout. Recent results and performance of device prototypes will be described.

9213-2, Session 1

High Energy Resolution Scintillators for Nuclear Nonproliferation Applications *(Invited Paper)*

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The goal of this work is to discover and develop effective new scintillators that can be used for the detection of illicit radioactive materials. A key performance criterion is the ability to reliably identify the specific gamma-ray signatures of radioactive elements, and energy resolution approaching 2% at 662 keV is required for this task. Small band gaps and minimal charge trapping are required to enable the high light output and proportional response to deposited gamma-ray energy necessary for good energy resolution. Our group has been investigating ternary metal halides and elpasolites activated with either divalent europium or trivalent cerium, and we have recently discovered several new compounds with excellent combinations of light yield and proportionality. Using the Bridgman technique, we have grown small single crystals of the new scintillators that have light yields up to ~95,000 photons/MeV and energy resolution as good as 2.4% at 662 keV. Considering the very early stage of development of these materials, it is reasonable to expect further improvement as the purity of the raw materials is improved and the crystal growth parameters are optimized. Some of the new compounds display very proportional photon responses, and measurements of the electron responses are planned. Current research is focused on understanding fundamental material properties related to optimizing the crystal growth of larger samples.

9213-3, Session 1

Electron thermalization and trapping in pure and doped scintillators studied by picosecond optical absorption

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In the track environment of a scintillator, spatial distributions of trapped carriers determined during gradient-driven transport of thermalizing carriers on the picosecond time scale can influence the proportionality between light yield and the initial particle energy in the whole light pulse. Picosecond spectroscopy of optical absorption induced by a short pulse of above-gap excitation reveals the free-carrier spectrum in real time, as well as delayed onset and rates of capture on holes, dopants, or defects depending on initial electron temperature. The laser excitation can be tuned to excite carriers that are initially very hot (~3 eV) relative to the band edges, or that are almost thermalized (~0.1 eV excess energy) at the outset. Undoped and doped samples of NaI:Tl(0%, 0.1%), CsI:Tl(0%, 0.01%, 0.04%, 0.3%), SrI2:Eu(0%, 0.2%, 0.5%, 3%), and GYGAG:Ce are studied by optical absorption and interband z scan experiments. The dependence of capture rates and diffusion coefficients on time through their dependence on electron temperature is included in simulations of local light yield in electron tracks for comparison to Compton coincidence and K-dip data.

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9213-4, Session 1

ZnSe:Te crystals grown by chemical vapor transport for scintillation application

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The development of ZnSe based scintillators using Tellurium doping as an iso-electronic activator is very attractive for low cost and low power instrumentation that uses Si photodetectors for readout. The reported high light output in ZnSe:Te reaches 80,000 ph/MeV. Several melt growth technique were used to grow bulk ZnSe:Te (M.P. 1552 ºC) single crystals. However, only high pressure Bridgman grown crystals demonstrated scintillation properties. Low cost approach like hot pressing ZnSe:Te powder and subsequent annealing was also investigated, but no scintillation properties were reported.

We have grown ZnSe:Te crystal using the chemical vapor transport (CVT) method with iodine as a carrier. The starting polycrystalline materials, ZnSe and ZnTe (2%), were loaded in a custom made CVT quartz ampoule. The growth was carried out in a 24-Zone furnace at a source temperature 900 ?C and substrate temperature 860 ºC for 20 days. The grown crystals were found to be polycrystalline and single crystal sample were harvested from it. The ZnSe:Te crystals showed a strong defect luminescence band center at 618 nm with both x-ray and laser excited

photoluminescence. A clear scintillation response was detected with 241Am alpha particle source using a Si avalanche photodetector (APD.)

9213-5, Session 1

Triplet harvesting plastic scintillators with neutron-gamma pulse shape discrimination

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Discrimination between neutrons and gamma-rays is typically accomplished by using inorganic or organic scintillators that are capable of pulse shape discrimination (PSD) such as Cs2LiYCl6:Ce and Diphenylanthracene. Although traditional plastic scintillators do not offer good neutron/gamma PSD, novel concepts being developed at Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratory (SNL), and Radiation Monitoring Devices, Inc. (RMD) are opening up pathways for plastic scintillators that provide better PSD.

One new concept being explored is to incorporate organometallic iridium into plastic scintillators. The idea is that these iridium compounds act as so-called triplet harvesting complexes that absorb the excited state triplet energy from the plastic scintillators and re-emit it at lower energy instead of being lost non-radiatively. As a result, the light yield is increased and PSD is improved.

In this paper we will show that these plastic scintillators have a relatively high light output (higher than BGO), a fast scintillation decay (< 10 ns) and exhibit very good neutron/gamma PSD with a Figure-of-Merit of $\geq$ 2.5 at 2.5 MeVee cut-off energy. Under X-ray excitation, the radioluminescence spectrum exhibits a broad band between 400 and 650 nm peaking at 470 nm which is well-matched to bialkali photomultiplier tubes and UV-enhanced photodiodes.

9213-6, Session 2

On polarization effect in high-resistivity CdTe-CdZnTe detectors *(Invited Paper)*

Arie Ruzin, Tel Aviv Univ. (Israel)

Practically from the very appearance of the CdTe detectors it was noticed that for some devices the performances deteriorate with the operation time. Thus the case of radiation detectors the general term “polarization” is often used to describe the related phenomena. It is generally agreed that the effects are caused by a buildup of a space charge in the device. Such space charge decreases the electric field causing a decrease in charge collection efficiency. It also increases the charge collection time which requires longer shaping times in the electronic circuitry, leading to increased electronic noise (mainly 1/f).

The nature of the space charge and the formation mechanisms remain vague. It is well documented that the effect is influenced by the semiconductor properties as well as by contacts. Namely, the polarization can be very pronounced with one metallization, and practically disappear with another (for the same semiconductor sample).

In this study finite element calculations were used to assess the impact of imperfect ohmic contacts, and compensating trap properties on the space charge formation and on the macroscopic device behavior. It is shown that low recombination velocity of otherwise ohmic contacts leads to a formation of space charge inside the device, but the space charge density is insufficient to affect the electric field distribution significantly without the presence of compensating levels.

9213-7, Session 2

Optimization of 200um pitch CZT detectors for future high-resolution X-ray instrumentation in astrophysics *(Invited Paper)*

Anna Zajczyk, Washington Univ. in St. Louis (United States); Marie Draper, Paul Dowkontt, Washington University in St. Louis (United States); Qingzhen Guo, Fabian Kislat, Henric Krawczynski, Washington Univ. in St. Louis (United States); Gianluigi De Geronimo, Shaorui Li, Brookhaven National Laboratory (United States); Matthias Beilicke, Washington Univ. in St. Louis (United States)

Cadmium Zinc Telluride (CZT) is the detector material of choice for the detection of X-rays in the hard X-ray energy band with excellent spatial and spectral resolution and without cryogenic cooling. Owing to recent breakthroughs in grazing incidence mirror technology, next-generation hard X-ray telescopes will achieve angular resolution between 5 and 10 arc seconds - about an order of magnitude better than that of the NuSTAR hard X-ray telescope. As a consequence, the next generation of hard X-ray telescopes will require pixelated hard X-ray detectors with pixels on a grid with a lattice constant of <= 240 um. Additional detector requirements include a low energy threshold of <5keV and an energy resolution of less than one keV. The science drivers for a high angular-resolution hard X-ray mission include studies and measurements of (i) black hole spins, (ii) the cosmic evolution of super-massive black holes, (iii) AGN feedback, and (iv) the behaviour of matter at very high densities. In this contribution, we report on the optimization of small-pixel CZT detectors at Washington University. In the second part of the talk, we describe the design and performance of the X-Calibur - a hard X-ray polarimeter utilizing CZT detectors. X-Calibur will be flown in the fall of 2014 and will measure the linear polarization of 10-80 keV X-rays.

9213-8, Session 2

Towards a deeper understanding of dislocations in detector-grade CdZnTe crystals

Ge Yang, Aleksey E. Bolotnikov, Yonggang Cui, Giuseppe S. Camarda, Anwar Hossain, Utpal Roy, Ralph B. James, Brookhaven National Lab. (United States); Chad S. Korach, Stony Brook Univ. (United States)

CdZnTe (CZT) has attracted much interest due to its promising applications in fabricating high-performance room-temperature X-ray- and gamma-ray- detectors. However, the presence of material defects, e.g. dislocations, remains a big concern, since they play a key role in determining the performance of CZT devices. In this work, we use a low-temperature spatially resolved micro-scale photoluminescence mapping (LSMPM) technique to probe the spatial variation of dislocation-related emissions. Experimental results with the above characterization method will be presented and discussed in detail. These results provide useful knowledge regarding the origin and nature of dislocations in detector-grade CZT crystals.

9213-9, Session 2

Effect of impurities near subgrain boundaries on CZT detector performance

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The goal of this study is to understand the origin and effect of subgrain boundaries and help to visualize the presence of a higher concentration of impurities, which might be responsible for the deterioration of the energy resolution and response uniformity. Several CZT detectors were evaluated by using the Micron-scale X-ray Detector Mapping (MXDM) system of beamline X27B at National Synchrotron Light Source (NSLS) of Brookhaven National Laboratory (BNL). The uniformity of the X-ray response maps for fabricated detectors is indicative of their overall performance. The results elucidate the importance of defects and confirm the role of impurities in the observed non-uniformities.

9213-10, Session 3

Improvements to the neutron detection crystal 6LiInSe2 *(Invited Paper)*

Ashley Stowe, Y-12 National Security Complex (United States); Brenden Wiggins, Vanderbilt Univ. (United States); Pijush Bhattacharya, Eugene Tupitsyn, Fisk Univ. (United States); Elan Herrera, University of Tennessee (United States); Eric D. Lukosi, The Univ. of Tennessee Knoxville (United States); Mike Groza, Liviu Matei, Fisk University (United States); Keivan Stassun, Vanderbilt Univ. (United States); Arnold Burger, Fisk Univ. (United States)

Chalcopyrite crystals of 6LiInSe2 have recently been shown to respond to gamma and thermal neutron radiation. Thus far, large crystals have been prepared although the charge collection efficiency has not been high enough for good energy resolution. Details studies have been conducted to understand the nature of such defects and improve both synthesis and crystal growth conditions in an effort to improve energy resolution needed for gamma spectroscopy as well as PSD for mixed gamma neutron fluxes. Laser induced breakdown spectroscopy and SEM-EDX mapping have revealed variation in the local stoichiometry of 6LiInSe2 indicating the presence Li-rich zones. Annealing techniques have improved both the yield of detection crystals from the boule as well as charge collect

9213-11, Session 3

Semiconductor neutron detectors using depleted uranium oxide *(Invited Paper)*

Craig Kruschwitz, Sanjoy Mukhopadhyay, David Schwellenbach, National Security Technologies, LLC (United States); Thomas T. Meek, Brandon Shaver, Taylor Cunningham, Jerrad Auxier, The Univ. of Tennessee Knoxville (United States)

This paper reports on recent attempts to develop and test a new type of solid-state neutron detector fabricated from uranium compounds. It has been known for many years that uranium dioxide (UO2), triuranium octoxide (U3O8) and other uranium compounds exhibit semiconducting characteristics with a broad range of electrical properties. We seek to exploit these characteristics to make a direct-conversion semiconductor neutron detector. In such a device a neutron interacts with a uranium nucleus, inducing fission. The fission products deposit their substantial energy, producing detectable electron-hole pairs. The high energy released in the fission reaction indicates that noise discrimination in such a device has the potential to be excellent. Schottky devices were fabricated using a chemical deposition coating technique to deposit UO2 layers a few microns thick on a sapphire substrate. Schottky devices have also been made using a single crystal from UO2 samples approximately 500 microns thick. Neutron sensitivity simulations have been performed using GEANT4. Neutron sensitivity for the Schottky devices was tested experimentally using californium-252 and americium-beryllium sources.

9213-12, Session 3

Investigation of a Lithium Indium Diselenide detector for neutron transmission imaging

Eric D. Lukosi, Elan Herrera, The Univ. of Tennessee Knoxville (United States); Ashley Stowe, Y-12 National Security Complex (United States); Robert Milbrun, Michael D. Richardson, The Univ. of Tennessee Knoxville (United States); Brenden Wiggins, Y-12 National Security Complex (United States); Arnold Burger, Fisk Univ. (United States); Louis Santodonato, Hassina Bilheux, Oak Ridge National Laboratory (United States)

The results of the research to be presented are focused on development and first experimental results of a spatially sensitive LISe gross neutron detector for neutron transmission imaging applications. Investigations into the crystal response, packaging, front end electronics, signal processing, image reconstruction, and modeling are considered. LISe crystals are characterized using CCE, TCT, and DLTS techniques using visible and ionizing radiation sources, to include the charge collection efficiency. Device fabrication, from pixel design, fabrication, and packaging is considered. The front end electronics are being developed from off-the-shelf components and are coupled to CAEN digitizers. The sensor developed will be tested for its speed and neutron transmission imaging capability at the CG-1D beam line at HFIR in Oak Ridge National Laboratory in June 2014.

9213-14, Session 3

Solid-state thermal neutron detectors based on hexagonal boron nitride epilayers

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Hexagonal boron nitride (hBN) epilayers have been synthesized by MOCVD on sapphire substrates and explored for thermal neutron detector applications [1]. The mobility-lifetime product and the thermal neutron absorption length have been characterized and the results indicate that these MOCVD grown hBN epilayers are suitable for detector fabrication. The fabricated hBN detectors exhibited extremely low dark currents. The reaction product pulse-height spectra measured under thermal neutron irradiation produced by a 252Cf source moderated by high density polyethylene block revealed distinguishable peaks corresponding to the product energies of 10B and neutron reaction with the 0.84 MeV 7Li peak being the most prominent. Furthermore, hBN detectors have a negligible response to gamma-rays and hence are expected to provide an excellent ability to discriminate between gamma and neutron radiation. 10B enriched hBN epilayers have been synthesized. A 4-fold reduction in the thermal neutron absorption length in 10B enriched hBN over natural hBN has been obtained. Our results indicate that hBN epilayers are very promising for realizing highly sensitive solid-state thermal neutron detectors with expected advantages resulting from semiconductor technologies, including compact size, light weight, ability to integrate with other functional devices, and low cost.

The efforts on hBN material growth and neutron detector fabrication are supported by DHS ARI Program (2011-DN-077-ARI048).

[1] T. C. Doan, S. Majety, S. Grenadier, J. Li, J. Y. Lin, H. X. Jiang, “Fabrication and characterization of solid-state thermal neutron detectors based on hexagonal boron nitride epilayers,” Nuclear Inst. and Methods in Physics Research Section A, 2014, in press.

9213-15, Session 4

CdTexSe1-x: A potential candidate for room-temperature radiation detector applications *(Invited Paper)*

Utpal Roy, Aleksey E. Bolotnikov, Giuseppe S. Camarda, Yonggang Cui, Anwar Hossain, Ge Yang, Ralph B. James, Brookhaven National Lab. (United States)

CdTexSe1-x has potential as a room-temperature radiation detector due to its several advantages over the conventional CdZnTe (CZT) material. The main advantage is the near-unity segregation coefficient of Se in the CdTe matrix, which results in higher compositional homogeneity of the grown ingot. In this talk, we will discuss the growth of CdTeSe crystals by various techniques, such as traveling heater method and vertical Bridgman technique. The grown ingots were analyzed for different defects, including Te inclusions/precipitations, sub-grain boundaries and dislocation networks, and their effects on the charge-transport characteristics were studied. Our experimental findings showed several advantages of CdTeSe over CZT in addition to the near-unity segregation coefficient of Se, including reduced concentrations of Te-inclusions/precipitations and subgrain boundaries and a higher degree of uniformity. Results on the charge-transport characteristics and device properties will be discussed in this presentation.

9213-16, Session 4

Investigation of the current-voltage characteristics, the electric field distribution and the charge collection efficiency in X-ray sensors based on chromium compensated gallium arsenide *(Invited Paper)*

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The paper presents the results of experimental studies of current-voltage characteristics, the distribution of the electric field and charge collection efficiency in the X-ray sensors based on gallium arsenide compensated with chromium (HR GaAs). Experimental samples were pad sensors with an active area of 0.1-0.25 cm2 and a thickness of the sensitive layer in the range of 250-1000 um. It is shown that in the voltage range of 0.02 – 1 V the current-voltage characteristics are determined by the bulk resistance of the sensor. A model of nonequilibrium charge carrier transport and estimation of Schottky barrier height in contact "metal-semiconductor" are presented. It has been established that the resistivity of the sensors reaches 1.5 GOhm?cm at room temperature, while a Schottky barrier height is 0.80-0.82 eV.

Investigation of the distribution of the electric field in the sensors was performed using the Pockels effect on the wavelength of infrared radiation 920 nm. Experimentally found that HR GaAs sensors electric field distribution is much more uniform compared with sensors based on SI GaAs: EL2. It was shown that in HR GaAs sensors the electric field has good time stability. There were not current oscillations connected with movement of electric field domains.

Analysis of the charge collection efficiency dependence on bias voltage when exposed to gamma rays with energies of 60 keV (241Am source) showed that HR GaAs material values of mobility lifetime product of nonequilibrium charge carriers are 6?10-5 cm2 /V?s and 3?10-7 cm2 /V?s for electrons and holes, respectively.

9213-17, Session 4

Scintillator efficiency study with MeV x-rays *(Invited Paper)*

Stuart A. Baker, Kristina K. Brown, Alden H. Curtis, Russell A. Howe, Stephen E. Mitchell, National Security Technologies, LLC (United States); Jeremy Danielson, Todd J. Haines, Los Alamos National Lab. (United States); Robert M. Malone, Steve S. Lutz, National Security Technologies, LLC (United States); Kris K. Kwiatkowski, Los Alamos National Lab. (United States); Aaron B. Luttman, National Security Technologies, LLC (United States)

We are investigating scintillator efficiency for MeV radiographic imaging. This paper discusses the modeled detection efficiency and measured brightness of a number of scintillator materials. An optical imaging camera records images of scintillator emission excited by a pulsed x-ray machine. The efficiency of various thicknesses of monolithic LYSO:Ce (cerium-doped lutetium yttrium orthosilicate) are being studied to understand brightness and resolution trade-offs to a range of micro-columnar CsI:Tl (thallium-doped cesium iodide) scintillator screens. The micro-columnar scintillator structure provides an optical gain mechanism which results in brighter signals from thinner samples. The trade-offs for brightness versus resolution in monolithic scintillators is straightforward. For higher-energy x-rays, thicker materials generally produce brighter signal due to x-ray absorption and the optical emission properties of the material. However, as scintillator thickness is increased, blur begins to dominate imaging system resolution due to the volume image generated in the scintillator thickness and the depth of field of the imaging system. We employ a telecentric optical relay lens to image the scintillator onto a recording CCD camera. The telecentric lens helps provide sharp focus through thicker-volume emitting scintillators. Stray light from scintillator emission can also affect the image scene contrast. We have applied an optical light scatter model to the imaging system to minimize scatter sources and maximize scene contrast.

9213-18, Session 4

Performance comparison of detector grade CdZnTe grown under varying non-stoichiometric growth conditions *(Invited Paper)*

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A number of Cd0.9Zn0.1Te crystals were grown by modified vertical Bridgman technique implementing accelerated ampoule rotation technique with different non stoichiometry in the melt. Two different sets of growths were conducted with 0.5 weight % and 7.5 weight % excess Te in the melt under otherwise identical growth parameters such as growth rate and interface gradient. All the grown crystals were doped with indium with the goal of obtaining semi insulating detector grade material. The crystals were characterized with respect to bulk electrical resistivity, single carrier mobility-lifetime (µ?e), spectrometric performance under 122 keV (57Co source) gamma irradiation and tellurium related second phase defects using infrared transmission microscopy. Crystals with higher amount excess tellurium in the melt were observed to be superior in terms of both electron and hole transport. Infrared microscopy results indicated lower secondary phase defects in the crystals grown with higher amount of excess Te in the melt. This observation could be correlated to the presence of relatively fewer grain boundaries and twins in these ingots caused by favorable thermo physical property of the higher excess Te melt. Result will be discussed of further reducing the growth rate.

9213-47, Session PMon

The neutron detectors based on oxide scintillators for control of fissionable radioactive substances

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In this work comparative response measurements and analyses of detection efficiency were carried out for oxide and alkali-halide scintillators exposed to fast and thermal neutrons from a 239Pu Be source. The experimentally-obtained fast neutron detection efficiency for heavy inorganic (oxide) scintillators (Z ? 50) was found to reach ~ 40-50%. One of the most probable interactions between matter and fast neutrons is the inelastic scattering reaction (n, n'?); by directly measuring the occurrence of this reaction in oxide scintillators, high-efficiency fast neutron detection can be achieved, especially in the case of oxide scintillators containing heavy atomic constituents. It is concluded that the use of heavy oxide scintillators, which at the same time are efficient gamma-detectors allows the creation of a highly efficient gamma-neutron detector, which enables the high efficiency of detection of fissionable radioactive materials.

In addition, detector design arrangements with associated electronic systems incorporating active protection methods were configured and tested, allowing a considerable (~103 times) reduction in the level of registration of scattered external high-energy gamma rays. Our experimental results show that the efficiencies of fast neutron detection by different scintillator crystals are proportional to the thickness of the crystal in the range of 10-40 mm, and do not depend on the thickness of the crystal in the range of 40-100 mm. It was demonstrated the correlation between detection efficiency and the effective atomic number Zeff of the crystalline scintillation material.

9213-48, Session PMon

Spectroscopic response of Cd(Zn)Te radiation detectors with a Schottky diode

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Spectroscopic properties of a number of CdTe detectors with Schottky contact were both investigated experimentally and simulated with computer code. The responses of surface-barrier Ni/CdTe/Ni detectors with a thickness of 0.5mm to gamma-rays from reference sources Am-241, Ba-133, Eu-152, Cs-137 and Co-60 were experimentally determined at room temperature. Low leakage current and substantially higher resistivity in investigated detectors allowed to increase the displacement voltage. This essentially improved the charge collection efficiency and ensured good energy resolution of detectors compared to Cd(Zn)Te detectors with ohmic contacts, especially at higher gamma-ray energies. In particular, the measured energy resolution at 661.67 keV (Cs-137) of the investigated detectors under 800 V of displacement voltage was better than 1.5%. For simulation of the response of Cd(Zn)Te detectors with the Schottky contact we modified our previous model of planar wide-gap detector realized in Geant4 code. Thus calculated response functions agreed satisfactorily the experimental data. The full width at half maximum of simulated photopeaks and calculated energy resolution of detectors as well correspond to experimental data. The proposed model also provided the possibility to determine for investigated detectors the products of mobilities and average lifetimes of electrons and holes. For investigated detectors the dependence of the efficiency of gamma-rays registration on their energy was calculated. Within the simulation model the influence of several parameters of the measuring equipment (detector leakage current, equivalent noise charge, displacement voltage) on the energy resolution of the surface-barrier detectors was investigated. Based on data of simulation the ranges of the measuring tract parameters were determined in which the energy resolution better than 1% can be reached at 661.67 keV.

9213-49, Session PMon

Informatic downselection of candidate detection materials from II-VI and III-V semiconductor classes

Kim F. Ferris, Pacific Northwest National Lab. (United States); Dumont M. Jones, Proximate Technologies, LLC (United States)

In this paper, we present the results of an informatic downselection of II-VI and II-V semiconducting compositions as candidate materials for gamma radiation detection materials. Identifying semiconducting compounds in these classes with CZT-like properties, requires a combination of strategies for property estimation and bounding. Informatic property estimations for band gap, density, and electron mobility form the fundamental materials screening criteria for a CZT-like semiconducting radiation detection material, but they also impose interacting constraints at the materials chemistry level. Successively, the property-based, coarse-grained downselection of these compounds focuses a series of series of better and more precise questions onto the semiconductor classes to assess the limits and bounds of physical properties. These property estimations when normalized against the target physical property form the basis for a composite performance map, which allows for comparative figures of merit for individual compositions across broad semiconductor composition classes. In terms of CZT-like materials, the downselection process tends to group potential materials into related compositional and chemistry families, e.g. composition: CZT-like semiconductors --> CdMnTe2 (CMT), materials chemistry: (TM)HgS2 where TM=transition metal, higher band gap --> greater electronegativity differences. Case examples of materials chemistries for ternary variations (eg. II-II-VI2 and IIII-VI2 compositions) and its III-V analogs will be presented to illustrate the interactions and constraining effects of correlated physical properties.

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9213-50, Session PMon

Development of an informatics model for the estimation of thermodynamic properties of radiation detection materials

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A "Hess-like" thermodynamic cycle featuring quantities amenable to informatic prediction and available reference quantities has been constructed for the prediction of heats of formation, and trained against a broad range of semiconducting and insulating materials. Akin to the volume-based thermodynamics models proposed by Jenkins and Glasser, these models are 'structureless', requiring little a priori information about specific crystal system and its atomic coordinates. Lattice energies were estimated using a linearized form of the Kapustinskii relationship (> 100 compounds, covering II-VI and III-V semiconductor and halide classes). To increase accuracy, a new model

for interatomic distances was developed which exhibits strong and robust correlation (R2=0.937, CV_R2=0. 918) to experimental values. The resulting lattice energy model shows similar strong agreement (R2=0.958, CV_R2=0. 957) compared against experimental Hess cycle quantities. Remaining quantities were obtained by the combination of standard reference data and estimation using modified Born models calibrated using partial least squares (PLS) techniques. The resulting thermodynamic cycle has shown utility for the estimation of thermodynamic 'makeability' of candidate semiconductor compositions and 'stability' against binary decompositions.

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9213-51, Session PMon

Recent progresses in scintillating doped silica fiber optics

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The recent progresses in the development and characterization of doped silica fiber optics for dosimetry applications in the modern radiation therapy, and for high energy physics experiments, are presented and discussed. In particular, the main purpose was the production of scintillating fiber optics with an emission spectrum which can be easily and efficiently distinguished from that of other spurious luminescent signals originated in the fiber optic material as consequence of the exposition to ionizing radiations (e.g. Cherenkov light and intrinsic fluorescence phenomena).

In addition to the previously investigated dopants (Ce and Eu), new rare earth elements, and possible co-dopants were considered for the scintillating fiber optic development. A study of the luminescent and dosimetric properties of these new systems was carried out by using X and gamma rays of different energies. Furthermore, a detailed investigation of the mechanisms responsible for possible sensitivity changes upon accumulated dose was performed.

9213-52, Session PMon

Explanation of the dark current in n-type Cd(Zn)Te semi-insulating crystals with ohmic contacts

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Ohmic contacts were deposited onto semi-insulating n-Cd(Zn)Te crystals. Measurements of the dark current-voltage characteristics at different temperatures were completed. The dependence of the resistivity of single-crystal semi-insulating n-Cd(Zn)Te on temperature was determined. The analysis of the electron and hole distributions from the electro-neutrality equation showed that the observed features of the electrical properties are due to the material's specific compensation processes. A technique for determining the ionization energy and energy level of the compensating deep-level defect, responsible for the dark conductivity in the material, is proposed. The measurements of the dark current in single-crystal semi-insulating n-Cd(Zn)Te with ohmic contacts is explained within the model of space-charge-limited currents.

9213-53, Session PMon

Purification of p-type CdTe crystals by thermal treatment

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The influence of prolonged heat treatment (PHT) effect on the concentration and acceptor energy level positions of p-CdTe samples at 670-780 K was studied. It was found that PHT at 690-750 K leads to a decrease in the concentration of electrically active centers, i.e. to the crystal's "self-cleaning" from the adverse effects of some contaminants. In samples where the conductivity was determined by the concentration of acceptors of the A1 type (EV + 0.03-0.05) eV, after PHT the conductivity becomes controlled by a deeper acceptor of the A2 type (EV + 0.13-0.14) eV, and both the charge carrier mobility ?p (at low temperature) and the ratio ??80/??300 significantly increase. This effect is due to the fact that during the PHT process, the A1 acceptors and compensating donors are removed from electrically active positions, most likely to their diffusion and trapping within the inclusions in the CdTe bulk, where they have little or no influence on carrier scattering and trapping.

9213-54, Session PMon

The REWARD project: real time wide area radiation surveillance with semiconductor detectors

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The EU 7FP REWARD project develops a novel real time wide area radiation surveillance system. Stationary and mobile units based on gamma and neutron detectors create a fine-meshed measurement network which is able to detect, identify and locate radioactive sources on a map.

1 cm x 1 cm x 1 cm (Cd,Zn)Te Coplanar Grid detectors identify different nuclides with an energy resolution of approximately 2 % FWHM at 662 keV. Thermoelectric cooling is used to stabilize the detectors at 20 °C. 3-D silicon sensors with perforations backfilled with a boron or lithium neutron converter are built around a 10 cm x 10 cm x 10 cm polyethylene cube, thermalizing and detecting neutrons. Additional silicon p-i-n diodes, covered with hydrogenated plastic, are used to identify fast neutrons.

Both detector subsystems are connected to a small, single board computer which collects neutron counts and gamma spectra and transmits the data periodically through GPS and TETRA network to a command and control center. In order to identify threats, a Central Monitoring System (CMS) will continuously analyze the radiation sensor information and correlate it with background data of the surrounding area. The REWARD scenarios range from nuclear terrorism threats, lost radioactive sources to radioactive contamination and nuclear accidents.

Neutron and gamma measurements have been performed at the ITN research facility in Portugal and the University of Freiburg, determining detection efficiency and background thresholds. General information about the project, as well as latest simulation and measurement results will be presented.

9213-55, Session PMon

THM growth of CZT in u-gravity on FOTON-M4

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The Russian FOTON mission offers the opportunity to grow crystals under gravitational influence reduced by 6 orders of magnitude during 60 days in space. The experiment capsule is launched by Russian Soyuz rocket in Baikonur, Kazakhstan.

Micro-gravity (µg) experiments are of interest in crystal growth since they enable the study of mass transport by reduction of gravity driven density convection to a negligible magnitude leading to a diffusion-dominated mass transport regime. In addition defined convection can be induced by applying a rotating magnetic field to the growth medium. The goal is estimating basic parameters for improving crystal growth on earth conditions.

Cadmium Zinc Telluride (CZT) for x-ray and ?-detection is of high interest in industry and science and is chosen to be included in the FOTON-M4 mission. The experiment is carried out by different companies and research institutes. CZT is grown by travelling heater method (THM) in a Tellurium-solution to achieve high resistivity material and low growth temperature. Zinc and dopant segregation can be reduced to a minimum. However certain improvements in defects regarding single crystallinity and reduction of Tellurium inclusions are to be made.

The µg-experiment is used to understand growth mechanisms including formation of defects and multiple grains. It is scheduled to June 2014. In parallel a reference experiment with same conditions and identical facility is performed on the ground. Both grown crystals will be characterized by HRXRD, EDX, GDMS, ICP and vapor pressure scanning and compared with simulations.

9213-56, Session PMon

Bulk resistivity changes in CZT with illumination from multiple energies

Aaron L. Washington II, Jonathan S. Wright, Martine C. Duff, Savannah River National Lab. (United States)

CdZnTe (CZT) exists as one of the most promising gamma radiation spectrometers in use today. As room temperature (RT) detector for gamma- and X-ray energies, it has significant advantages over current industrial detection methods, such as silicon and germanium detectors. Manipulation of the internal electric field in CdZnTe crystals using illumination as a post growth method is investigated as a function of bulk resistivity using I-V measurements. Optical de-trapping of charge carriers, using IR illumination, shows an increase current that correlates to a change in the bulk resistivity of the crystal. Additionally, this change in resistivity can be correlated to different degrees of charge trapping at multiple wavelengths and powers of illumination. We have systematically measured the change in bulk resistivity with illumination as a function of wavelength and power via the Pockels effect.

In this report, we demonstrate an ability to manipulate the internal electric field of CZT using multiple wavelength and optical powers of light illumination on the crystal surface at RT. The illumination also causes a significant change in the bulk resistivity of CZT that varies based on the wavelength and optical power even in the sub-bandgap regime.

9213-57, Session PMon

Characterization of high-resistivity CdTe crystals grown under component overpressures of cadmium for radiation detector applications

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Detector-grade CdTe single crystals with resistivities ≥5x10^9 Ω-cm have been grown by a modified Bridgman method using zone-refined precursor materials (Cd and Te) under various Cd overpressures. The grown crystals showed good charge-transport properties (µ?_e ~ 5x10^-3 cm^2/V.s, µ?_h ~8.5x10^-3 cm^2/V.s) and significantly reduced Te precipitates compared with crystals grown without Cd-overpressures. The crystal growth conditions with Cd-overpressures for the Bridgman system were optimized by computer modeling and simulation and applied to crystal diameters of ~38 mm (1.5") and 76 mm (3"). Details of the CdTe crystal growth conditions, structural, electrical, optical, and spectroscopic characterization, detector fabrication, and testing using 241^Am (60 keV) and 137^Cs (662 keV) radiation sources will be presented.

9213-58, Session PMon

Characterization of icosahedral boron arsenide (B12As2) for thermal neutron detection

Yonggang Cui, Aleksey E. Bolotnikov, Giuseppe S. Camarda, Fernando Camino, Anwar Hossain, Utpal Roy, Dong Su, Yang Ge, Brookhaven National Lab. (United States); James H. Edgar, Clinton E. Whiteley, Ugochukwu Nwagwu, Kansas State Univ. (United States); Ralph B. James, Brookhaven National Lab. (United States)

Global helium-3 shortage has motivated researchers to seek alternative materials for thermal neutron detection, especially solid-state materials, which have potential advantages of compact size, easy maintenance and low cost. Boron compound semiconductors are especially good candidates because the B-10 isotope has large thermal neutron capture cross-section (3840 barns) and is readily abundant (20% of natural boron). In addition, in such compound materials, neutron capture and ionization generation take place in the same media, allowing full absorption of secondary particles and complete charge collection. Among all the candidate materials, icosahedral boron arsenide (B12As2) is particularly appealing for thermal neutron detection due to its wide band-gap (3.4 eV) and good hole-transport properties. Currently we are evaluating bulk crystals grown from a metal flux solution by white-beam x-ray diffraction topography (WBXDT) to determine the crystalline structure of the crystals and the presence of extended defects (e.g., twins, grain boundaries and secondary phases); scanning electron microscopy (SEM) to analyze their elemental composition; transmission electron microscopy (TEM) for detailed investigations of the growth mechanisms; and electron energy loss spectroscopy (EELS) to measure the impurities in the samples. In this presentation, we will discuss the characterization of these crystals and present our test results.

9213-59, Session PMon

Characterization of cadmium manganese telluride (Cd1-xMnxTe) crystals grown by floating zone method

Anwar Hossain, Genda Gu, Aleksey E. Bolotnikov, Giuseppe S.

Camarda, Yonggang Cui, Utpal Roy, Ge Yang, Ralph B. James, Brookhaven National Lab. (United States)

Recently, Cadmium Manganese Telluride (CMT) emerged as a promising material for room-temperature X- and gamma-ray detectors. It offers several potential advantages over CdZnTe. Among them is its optimal tunable band gap ranging from 1.7-2.2 eV, and its relatively low (< ~50%) content of Mn compared to that of Zn in CdZnTe that assures this favorable band-gap range. Another important asset is the segregation coefficient of Mn in CdTe that is approximately unity compared to 1.35 for Zn in CdZnTe, so ensuring the homogenous distribution of Mn throughout the ingot; hence, a large-volume stoichiometric yield is attained. However, our studies revealed several material defects primarily related to growth processes that are impeding the production of large single crystals with high resistivity and high mobility-lifetime product. In this work, we characterized various defects in materials grown by the floating zone method, including Te inclusions, twins and dislocations, using our unique facilities. We also fabricated detectors from selected CMT crystals and tested their detector performance. We will present detailed findings on the material properties and the performance of fabricated CMT detectors.

9213-60, Session PMon

Mechanism of laser-induced doping and formation of CdTe-based barrier structures for x-/gamma-ray detectors

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Application of room temperature CdTe X/gamma-ray detectors in medicine, security, astronomy, spectroscopy and other areas, requiring high energy resolution, has led to development of CdTe-based diode structures. The problem of incomplete collection of photon-generated carriers that limits the detector performance can be overcome if a barrier contact is used instead of an Ohmic one. Thus, application of high bias voltage provides high charge collection and abrupt electrical barrier prevents increasing of leakage current in a diode. However, diode type detectors are commonly affected by the bias-induced polarization phenomenon that leads a progressive decrease in their sensitivity and energy resolution. Recently, significant improvement have been achieved in the properties of detectors with a p-n junction formed by the laser-induced solid-phase doping which was used to suppress the self-compensation effect and introduce In impurity atoms in a thin surface layer of semi-insulating p-like CdTe crystals. The surface area of CdTe(111) crystals pre-coated with an In film was irradiated with nanosecond pulses in liquid environment. The obtained M-p-n structured In/CdTe/Au detectors have shown high energy resolution (FWHM ~ 0.7%@662 keV). Despite of this, there are problems related to inhomogeneity and instability of electrical and spectral characteristics of In/CdTe/Au diodes. In order to increase the yield of detectors with acceptable parameters, the mechanism of laser-induced solid-phase doping of the semiconductor in liquid environment has been investigated. The action of laser-induced stress and shock waves, processes of laser-stimulated point defect formation and diffusion of dopant atoms into the surface region of CdTe crystals are discussed.

9213-61, Session PMon

Photon crosstalk in pixel array for x-ray imaging

MyungSoo Kim, Giyoon Kim, Dong-uk Kang, Dae-Hee Lee, Gyuseong Cho, KAIST (Korea, Republic of)

A large-area X-ray CMOS image sensor (LXCIS) is widely used in mammography, non-destructive inspection, and animal CT. For LXCIS, in spite of weakness such as low spatial and energy resolution, a Indirect method using scientillator like CsI(tl) or Gd2O2S is still well-used because of low cost and easy manufacture. A photo-diode for X-ray imaging has large area about 50 ~ 200 um as compared with vision image sensors. That is because X-ray has feature of straight and a light emittance of a scientillator is very small. Moreover, notwithstanding several structure like columnar, the scientillator still emit a diffusible light. This diffusible light from scientillator can make photon crosstalk in X-ray photo-diode array because of a large incidence angle. In vision image sensors, they have micro lens for gathering the photons to small sized photo-diode. In this study, we simulated and will test the photon crosstalk problem and make a suggestion about optimized metal structure, which is for pixel separation. The simulation is done by 2-D TCAD of SILVACO and the test chip have been fabricated by 0.18 um 1P5M process by Hynix in republic of Korea.

9213-19, Session 5

Advances in the growth of alkaline-Earth halide single crystals for scintillator detectors *(Invited Paper)*

Lynn A. Boatner, Joanne O. Ramey, Oak Ridge National Lab. (United States); James A. Kolopus, Oak Ridge National Lab. (United States) and UT-Battelle LLC (United States); John S. Neal, Oak Ridge National Lab. (United States); Nerine J. Cherepy, Stephen A. Payne, Lawrence Livermore National Lab. (United States); Arnold Burger, Emmanuel Rowe, Pijush Bhattacharya, Fisk Univ. (United States)

The “rediscovery” of scintillation in SrI2:Eu2+ in 2008 and the achievement of outstanding scintillator performance through the application of improved purification, compositional, and crystal growth techniques to this material has stimulated new research efforts on other alkaline-earth-halide scintillators. Like SrI2:Eu2+, an additional scintillator, CaI2:Eu2+, was also originally discovered by Robert Hofstadter, however serious problems quickly arose that were associated with the growth of large un-cracked single crystals of this material due to its lamellar, mica-like structure. Problems with the cracking of crystals during growth can also occur in the case of the orthorhombic-structure SrI2:Eu2 scintillator. Here we report on recent advances in the Bridgman growth of un-cracked SrI2:Eu2+ crystals and on progress in the growth of large single crystals of CaI2:Eu2+. Molten (or solid) calcium iodide does not adhere to modern glassy carbon Bridgman crucibles - so there are no “sticking” problems and associated differential thermal-contraction-induced crystal/crucible stresses on cooling that could result in cracking/cleaving of the lamellar structure of CaI2. We have recently successfully applied Bridgman growth using glassy carbon crucibles to the growth of CaI2:Eu2+. This approach combined with the use of molten salt filtration has successfully produced promising un-fractured CaI2:Eu2+ single crystals. Additionally, in the case of the growth of SrI2:Eu2+ crystals, we have developed a growth-charge melt processing protocol that has yielded significant improvements in the yield of un-cracked single crystals of this material. The details of these procedures and their application to other alkaline-earth host materials will be described in detail here.

9213-20, Session 5

Toward a user’s toolkit for modeling scintillator proportionality and light yield *(Invited Paper)*

Qi Li, Xinfu Lu, Richard T. Williams, Wake Forest Univ. (United States)

Most of the physics of nonproportionality lies in the host-transport and transfer-to-activator term S in the well-known 3-term product for light

yield by Lempicki et al. [1] The main physical phenomena involved are carrier diffusion, trapping, drift in internal electric fields, and nonlinear rates of radiative and nonradiative recombination – nothing particularly exotic. Some complexity is added by the now well-established fact that the electron temperature is changing during important parts of the physical processes listed above. It has consequences, but is tractable by application of electron-phonon interaction theory and first-principles calculation of trap structures checked by experiment. Determination of coefficients and rate "constants" as functions of electron temperature Te for diffusion, D(Te(t)); capture on multiple radiative and nonradiative centers, A1i(Te(t)); bimolecular exciton formation, B2(Te(t)); and nonlinear quenching, K2(Te(t)), K3(Te(t)) in specific scintillator materials will enable computational prediction of energy-dependent response from standard rate equations solved in the electron track for initial excitation distributions calculated by standard methods such as Geant4. Te(t) itself is a function of time. Progress in calculating electronic structure of traps & activators, diffusion coefficients and rate functions, and testing the model will be described.

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[1] A. Lempicki, A. J. Wojtowicz, and E. Berman, "Fundamental limits of scintillator performance," Nucl. Instr. and Meth. A, vol. 333, pp. 304-311, 1993.

9213-21, Session 5

Radiation response of inorganic scintillators: insights from Monte Carlo simulations *(Invited Paper)*

Micah Prange, Dangxin Wu, Yulong Xie, Luke W. Campbell, Fei Gao, Sebastien Kerisit, Pacific Northwest National Lab. (United States)

Understanding the physics of elementary processes that give rise to scintillator performance is a primary driving force sustaining the search for new scintillator materials. Monte Carlo-based (MC) models have been developed at the Pacific Northwest National Laboratory to gain fundamental insights into the scintillation process by following the fate of individual electron-hole pairs from initial creation to recombination and photon emission. In particular, a MC model of electron thermalization, which simulates electron scattering with both optical and acoustic phonons, has been implemented in our atomistic kinetic MC model of scintillation; thus allowing us to probe nonlinear quenching mechanisms. Parameterization of nonlinear quenching mechanisms is achieved through the use of recent experimental data on the photon density response of inorganic scintillators thus enabling more realistic simulations of scintillator nonproportionality, an important performance characteristic. Indeed many inorganic scintillators display some degree of light yield nonproportionality following ?-ray excitation, which is one of the main sources that degrade their intrinsic energy resolution. In this contribution, application of these models to pure and doped alkali and alkaline-earth halide scintillators (CsI, NaI, SrI2, CaF2, and BaF2) will be presented, highlighting where the models have allowed for elucidating the elementary processes underlying the kinetics and efficiency of scintillation. Implications for the phenomenon of nonproportionality in scintillator light yield will also be discussed.

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9213-22, Session 5

Search for high-performance scintillator candidates among the electronic structures of mixed halides and other compounds *(Invited Paper)*

Koushik Biswas, Arkansas State Univ. (United States)

The application of advanced theory and modeling techniques has become an essential component to understand material properties and hasten the design and discovery of new ones. This is true for diverse applications. Therefore, current efforts aimed towards finding new scintillator materials are also aligned with this general predictive approach. The need for large scale deployment of efficient radiation detectors requires us to find high-performance, yet low-cost scintillators. While Tl-doped NaI and CsI are still some of the widely used scintillators, there are promising new developments, for example, Eu-doped SrI2 and Ce-doped LaBr3. Although the newer candidates have excellent light yield and good energy resolution, challenges persist in the growth of large single crystals. Within this context, we will discuss a targeted and coordinated theoretical and experimental search to discover new scintillator hosts, informed by the design rules for scintillator performance. Factors influencing this search include possible cubic structure for ease of growth, moderate melting point, complex basis of heavy elements, and earth-abundant non-toxic constituents. In this regard, mixed crystals or solid solutions of known and potential scintillators seem to be attractive candidates. We will discuss a theoretical basis for anticipating improved proportionality as well as light yield in solid solutions of certain systems, particularly mixed alkali halides. Co-doping of existing scintillators and activated "semiconductor scintillators" (e.g. ZnSe:Te) will also be discussed.

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9213-23, Session 5

Strontium iodide instrument development for gamma spectroscopy and radio-isotope identification

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Development of the Europium-doped Strontium Iodide scintillator, SrI2(Eu), has progressed significantly in recent years. SrI2(Eu) has excellent material properties for gamma ray spectroscopy: high light yield (>80,000 ph/MeV), excellent light yield proportionality, and high effective atomic number (Z=49) for high photoelectric cross-section. High quality 1.5" and 2" diameter boules are now available due to rapid advances in SrI2(Eu) crystal growth. In these large SrI2(Eu) crystals, optical self-absorption by Eu2+ degrades the energy resolution as measured by analog electronics, but we mitigate this effect through on-the-fly correction of the scintillation pulses by digital readout electronics. Using this digital correction technique we have demonstrated energy resolution of 2.9% FWHM at 662 keV for a 4 in3 SrI2(Eu) crystal, over 2.6 in long. Based on this digital readout technology, we have developed a detector prototype with greatly improved radioisotope ID capability compared to Sodium Iodide, NaI(Tl). The superior detection efficiency and energy resolution relative to NaI(Tl) improve both the time to identify a radioactive isotope and the reliability of that identification.

9213-24, Session 6

Observations of extended defects in large-volume detector-grade CdZnTe crystals

Anwar Hossain, Aleksey E. Bolotnikov, Giuseppe S. Camarda, Yonggang Cui, Utpal Roy, Ge Yang, Ralph B. James, Brookhaven National Lab. (United States)

Over the past decade, many problems have been identified and resolved pertaining to CdZnTe detectors, taking the technology to a more mature stage in commercialization and deployment. However, their widespread usage still remains limited by the low yield of detector-grade crystals and associated high cost as compared to common scintillators. Though high-resistivity large-volume CZT single crystals are available, their performance is still lower than the theoretical limit due to unresolved crystal defects. Presently, the defects in such large CdZnTe crystals correspond mainly to non-stoichiometry, impurities and extended defects (e.g., dislocations, micro-grains, and Te-rich secondary phases). In this work, we employed a variety of sophisticated tools to characterize commercial large-volume as-grown and annealed CZT crystals. We tracked the network of dislocations including the Te-rich secondary phases and micro-grains along the oriented crystals, assessed the material non-uniformity over the detectors' area, and then characterized the morphology of the Te-rich secondary-phase defects. We collected high spatial-resolution charge-collection maps of some selected planar- and pixilated-detectors, and determined the influence of the existing defects on their performance. Here, we detail our recent observations of various defects in such large-volume detector crystals and their influence on the detector's performance and how these issues can be resolved effectively.

9213-25, Session 6

Development and characterization of cadmium telluride pixel detectors with custom ASIC

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We are developing imaging Cadmium Telluride (CdTe) pixel detectors that have potential application for astrophysical NASA Explorer and Probe-class missions utilizing wide field and focusing instruments. Our hybrid-sensor consist of a CdTe detector 1.5mm thick and 2cm x 2cm in area with segmented anode contacts directly bonded to an application specific integrated circuit (ASIC). We have utilize a custom low noise, low power ASIC circuit developed for the Nuclear Spectroscopic Telescope Array (NuSTAR) mission which was successfully launched on June 13, 2012 as a first hard X-ray focusing telescope in space. While, NuSTAR employed detector is Cadmium Zinc Telluride (CZT) detectors, for this study, we used the CdTe detector, fabricated by Acrorad (Okinawa, Japan). These detectors used segmented Schottky blocking contacts on a 604-micron pitch in a 32 x 32 array, that provided low leakage current and also enabled readout of the anode side. The CdTe detector is bonded to the ASIC using epoxy-gold stud interconnections. In this paper, we report on the status of our ongoing development efforts, and describe results from detailed X-ray testing of the device, including uniformity of spatial and spectral response.

9213-26, Session 6

Modeling the migration of tellurium-rich second-phase particles in cadmium zinc telluride (CZT) via temperature gradient zone melting (TGZM)

Kerry Wang, Andrew Yeckel, Jeffrey J. Derby, Univ. of Minnesota (United States)

Crystals of cadmium zinc telluride (CZT) typically exhibit significant populations of large (10 micron and above) tellurium-rich particles that are deleterious to the performance of semiconductor radiation detectors. While it is well understood that melt growth of CZT can produce crystalline material that is supersaturated with tellurium, providing a thermodynamic basis for the existence of these second-phase particles, their formation mechanisms are not well understood.

As an alternative to preventing particle formation during the growth process (which may not be possible), an interesting post-growth treatment may provide a means to higher-quality crystals. Namely, these large, tellurium-enriched, secondary-phase particles can be induced to move away from a region of grown crystal and accumulate elsewhere, leaving higher-quality regions that contain far fewer particles. This accomplished by heating the sample to slightly above the eutectic temperature (the melting point of the second-phase particles) and engineering a temperature gradient across the sample. Under such conditions, the now-liquid particle dissolves on the hot side and re-solidifies on the cool side, with a net effect of migrating toward the hotter region. This process is termed "temperature gradient zone melting," or TGZM.

We will present the formulation and implementation of models that employ the finite element method to solve for particle migration via TGZM. We will also present initial results to verify the model and identify the dominant physical interactions involved in this process.

9213-27, Session 6

Structural and electronic properties of contacts on chemically polished CdZnTe for radiation detector applications

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State-of-the-art, room temperature, high resolution x-ray and gamma-ray detectors are usually based on CdZnTe semiconductors. The structural and electronic properties of CdZnTe surfaces, especially surface/contact metal interfaces, have a significant impact on radiation detector performance, such as leakage current, signal to noise ratios and energy resolution, particularly for relatively soft x-ray photons and large pixilated arrays. Atomically smooth and defect-free surfaces are desirable for high performance CdZnTe-based detectors; chemo-mechanical polishing is typically preformed to produce such smooth CdZnTe surfaces. The choices of contact material and deposition technique determine the electronic properties to a large extent. We present a detailed study on the structural and electronic properties, hence detector performance, of various metal contacts deposited by electron-beam and sputtering deposition techniques on chemically polished (CP) CdZnTe surfaces of about 1 nm roughness. X-ray photoemission spectroscopy results indicate that contacts deposited on CP-finished CdZnTe surfaces are oxide-free and no sign of atomic intermixing is observed. Scanning electron micrographs show a smooth and defect-free interface. I-V measurements show either ohmic or rectifying behaviour depending on the contact metal and deposition procedure. Energy resolution measurements of fabricated detectors will also be presented.

9213-28, Session 7

Using position-sensing strips to enhance the performance of virtual Frisch-grid detectors *(Invited Paper)*

Aleksey E. Bolotnikov, Giuseppe S. Camarda, Yonggang Cui, Gianluigi De Geronimo, Jack Fried, George Mahler, Matthew Petryk, Utpal Roy, Emerson Vernon, Ge Yang, Ralph B. James, Brookhaven National Lab. (United States)

We report on the development of arrays of virtual Frisch-grid CdZnTe (CZT) detectors for spectroscopy and imaging of gamma rays. Our detector design employs 6x6x15 mm3 (or taller) CZT crystals encapsulated into polyester shells with a 5-mm-wide shielding electrode placed around the anode. The basic array (module) consists of 36 detectors grouped into 3x3 sub-arrays, each having 2x2 detectors with a common cathode made up by connecting together the cathodes of the individual detectors. Each module is coupled with its front-end ASIC chip, which captures signals from 36 anodes and 9 cathodes. The results from testing the first integrated modules and readout electronics will be presented. The performance of the virtual Frisch-grid detectors can be further enhanced by dividing the shielding electrode into 4 position-sensing strips. The X-Y position information allow for more accurate corrections of charge losses caused by crystal defects. As we will describe in the talk, this feature can significantly improve the performance of detectors fabricated from typical CZT material and, thus, extend their acceptance boundaries, leading to an increase in the yield and an expected decrease in cost.

9213-29, Session 7

Review of current neutron detection systems for emergency response

Sanjoy Mukhopadhyay, Richard J. Maurer, Paul P. Guss, Craig Kruschwitz, National Security Technologies, LLC (United States)

Neutron detectors are used in a myriad of applications—from safeguarding special nuclear materials (SNM) to determining lattice spacing in soft materials. The transformational changes taking place in neutron detection and imaging techniques in the last few years are largely being driven by the global shortage of helium-3 (3He). This article reviews the status of neutron sensors used specifically for SNM detection in radiological emergency response. These neutron detectors must be highly efficient, be rugged, have fast electronics to measure neutron multiplicity, and be capable of measuring direction of the neutron sources and possibly image them with high spatial resolution.

Neutron detection is an indirect physical process: neutrons react with nuclei in materials to initiate the release of one or more charged particles that produce electric signals that can be processed by the detection system. Therefore, neutron detection requires conversion materials as active elements of the detection system; these materials may include boron-10 (10B), lithium-6 (6Li), and gadollinium-157 (157Gd), to name a few, but the number of materials available for neutron detection is limited. However, in recent years, pulse-shape-discriminating plastic scintillators, scintillators made of helium-4 (4He) under high pressure, pillar and trench semiconductor diodes, and exotic semiconductor neutron detectors made from uranium oxide and other materials have widely expanded the parameter space in neutron detection methodology. In this article we will pay special attention to semiconductor-based neutron sensors. Modern micro-fabricated nanotubes covered inside with neutron converter materials and with very high aspect ratios for better charge transport will be discussed.

9213-30, Session 7

A dual-energy transmission detector for vehicle scanning using wavelength-shifting fibers

Seth Van Liew, Ming Zhang, American Science and Engineering, Inc. (United States)

Detecting and identifying contraband in a drive-through portal x-ray screening system is of high demand at ports, borders, and other checkpoints. We will present a drive-through transmission detector based on scintillator sheets and wavelength-shifting fibers. This inexpensive system provides dual energy material information, utilizing an algorithm that removes the metal skin of the vehicle for true organic, inorganic, and metal discrimination of the cargo. It is low dose, allowing for scanning of the driver. The transmission detector is less than one inch thick, which allows rapid deployment without addition trenches or construction. This portal is designed for vehicle traffic five times greater than the previous generation and performs an average scan in less than two seconds. It is relatively insensitive to alignment issues, as it is not a segmented detector and is wider than the beam. This portal uses a flying-spot x-ray pencil beam, which in addition to transmission imaging, also provides concurrent Compton backscatter imaging with the same beam. The previous generation transmission system was heavier, thicker, provided no material identification, needed to be installed in a trench dug in the ground, and was designed for vehicle traffic at low speed. This new system is highly-configurable, with adjustments that can be easily made to maximize desired parameters such as penetration, thin material identification, and other customer requests.

9213-31, Session 7

Characterization of the ePix100 prototype: a front-end ASIC for second-generation LCLS integrating hybrid pixel detectors

Pietro Caragiulo, Angelo Dragone, Bojan Markovic, Ryan Herbst, Kurtis Nishimura, Benjamin A. Reese, Philip A. Hart, Sven C. Herrmann, Gabriel Blaj, Julie Segal, Astrid Tomada, Jasmine Hasi, Gabriella A. Carini, Christopher J. Kenney, Gunther Haller, SLAC National Accelerator Lab. (United States)

ePix100 is the first variant of a novel class of integrating pixel ASICs architectures optimized for the processing of signals in second generation LINAC Coherent Light Source (LCLS) X-Ray cameras. ePix100 is optimized for ultra-low noise application requiring high spatial resolution. Based on the ePix common platform, the variant has 50umx50um pixels arranged in a 352x384 matrix, a resolution of 50e- r.m.s. and a signal range of 35fC (100 photons at 8keV). In its final version it will be able to sustain a frame rate of 1kHz. A first prototype has been fabricated and characterized. Performance in terms of noise, linearity, uniformity and cross-talk will be discussed at the meeting, together with preliminary measurements with bump bonded sensors.

9213-32, Session 7

Waveform discrimination counter for radiation detector

Toru Aoki, Shizuoka Univ. (Japan); Akifumi Koike, Takaharu Okunoyama, Hisashi Morii, ANSeeN Ltd. (Japan); Hidenori Mimura, Shizuoka Univ. (Japan)

We developed the radiation-detector-oriented waveform discrimination equipment, which is small, easy and portable. When it is a signal with which waveform form differs, even if amplitude differs, it can discriminate from two or more waveform form.

The waveform difference was able to be distinguished by calculation of the value of peak and decreased after the definite period of time by the peak from the outputted pulse from an analog integration differentiation circuit.

When using general SCA, ROI had to be set up for peak value and an attenuation value by respectively different delimitation for every pulse, but since ROI of both operation result was freely set up by digital operation, highly precise waveform discrimination was attained.

It is applicable to different CLIC etc. of a luminescence waveform by radiation type.

9213-33, Session 8

Experimental identification of deep level defects in semi-insulating CdZnTe

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The existence of deep level defects has been claimed to explain the Fermi-level pinning for semi-insulating CZT materials. The space charge and capacitance of MIS (metal-insulator-semiconductor) devices change on the external bias due to the accumulation, depletion, and inversion process in semiconductor. Insulating layers for CZT MIS devices was formed on the well-polished CZT surface with ammonium fluoride solution. An analysis of differential capacitance for low and semi-insulating CZT material found to be strongly affected by the existence of deep levels. In addition, differential capacitance curve for semi-insulating CZT exhibits a peak in a middle of bandgap which considered as deep levels defects.

9213-34, Session 8

Chemical treatment of CdZnTe radiation detectors using hydrogen bromide and ammonium-based solution

Ifechukwude O. Okwechime, Stephen Egarievwe, Alabama A&M Univ. (United States); Anwar Hossain, Brookhaven National Lab. (United States); Zaveon M. Hales, Alabama A&M Univ. (United States); Ralph B. James, Brookhaven National Lab. (United States)

Cadmium zinc telluride (CdZnTe) radiation detectors incur surface damages that occur during dicing and polishing which often result in increased leakage current that limits the performance of the detector. An effective method of removing the surface damages and thus reducing the leakage current is through the use of chemical treatments. The effects reported in this study include: chemical polishing with a mixture of hydrogen bromide (48% concentration) in hydrogen peroxide (30% concentration) and ethylene glycol followed by passivation with ammonium fluoride in hydrogen peroxide solution. The effects of the chemical treatments on the current-voltage measurements and spectral response were monitored over a 2-week period. X-ray photoelectron spectroscopy (XPS) data were also obtained. The resistivity of the treated CdZnTe samples is in the order of power 10 ohms-cm. The current in the I-V measurements increased rapidly immediately following the chemical polishing and surface passivation, and decreased steadily afterwards. The spectral response results show that the 59.5-keV peak of Am-241 was stable in the same position over the test period.

9213-35, Session 8

High-efficiency CdTe and GaAs sensors for x-ray imaging

Simon Procz, Michael Fiederle, Alex Fauler, Frank Fischer, Albert-Ludwigs-Univ. Freiburg (Germany); Thomas Koenig, Elias Hamann, Karlsruher Institut für Technologie (Germany)

Innovative detector systems for non-destructive material analysis and for medical diagnosis are an important development to improve the performance and the quality of examination methods. For a number of years now photon-counting X-ray detectors are being developed to process incoming X-ray photons as single events.

Beside the photon counting ASIC a key component is the sensor material. Due to its homogeneity and stability Silicon is the standard semiconductor sensor material for pixelated X-ray detectors. It provides a very high detector and image quality for investigations with low energy X-rays < 30 keV. For medical imaging and non-destructive high Z material analysis it is not the optimal sensor material because of its low Z.

The compound semiconductor sensor materials GaAs (Z= 31, 33) and CdTe (Z= 48, 52) have a higher Z than Si (Z= 14) and there a better X-ray absorption efficiency. Recent progress in growing and processing of these materials makes them interesting as efficient sensor material for X-ray imaging applications.

For investigations on these sensor materials they were bump bonded to Medipix readout ASICs. The Medipix has 256x256 pixels with a pixel pitch of 55x55 µm? and features adjustable energy thresholds allowing multispectral X-ray imaging. The Medipix chip is under continued development by the Medipix Collaborations at CERN.

The sensor materials Si, GaAs and CdTe have been investigated for X-ray imaging applications. The efficiency, the homogeneity, the spatial resolution (MTF) and high flux behavior of these sensor materials will be presented as a comparison.

9213-36, Session 8

Analysis of the growth of cadmium zinc telluride (CZT) by the traveling heater method (THM)

Jeff H. Peterson, Andrew Yeckel, Jeffrey J. Derby, Univ. of Minnesota (United States)

The traveling heater method (THM) has enjoyed particular success for the growth of cadmium telluride (CdTe) and cadmium zinc telluride (CZT). In THM, unlike in conventional melt growth, crystalline material grows from a liquid phase that is enriched by a suitable solvent. Notably, crystalline CZT is grown from a liquid phase that contains excess tellurium. This solvent phase is produced in a liquid zone that is simultaneously dissolving a charge of CdTe or CZT as it is moved via a traveling heater. Desirable attributes of THM include lower growth temperatures and material that contains less excess tellurium than material grown from the melt. However, growth rates in THM are typically orders of magnitude smaller than those obtained in melt growth processes. In addition, THM is inherently more complicated than melt growth methods, since compositional effects, including both phase equilibria and phase change kinetics, are of paramount importance.

In this presentation, we formulate a comprehensive mathematical model for the THM process and present initial results on THM growth characteristics, such as interface shape, thermal gradients, interfacial stability, and crystal composition (both tellurium excess and zinc distribution). We will examine parametric process sensitivity to factors such as growth rate, heater profile, and size of the melt zone. In particular, we examine several phenomena that limit achievable growth rates in this system, such as constitutional supercooling, growth kinetics, and dissolution rates of the feed into the zone. Preliminary comparison with experimental systems will also be presented.

9213-37, Session 9

First-principles study of halide-based semiconductor radiation detection materials *(Invited Paper)*

Mao-Hua Du, Oak Ridge National Lab. (United States); Koushik Biswas, Arkansas State Univ. (United States); David J. Singh, Oak Ridge National Lab. (United States)

Halides are usually not used as electronic materials due to their inferior transport properties. However, a number of halide-based semiconductor materials (e.g., TlBr, Tl6SeI4, CsPbBr3, etc.) have been reported to exhibit exceptionally good carrier transport properties and have been investigated as potential radiation detection. In this paper, first-principles study of defects and dielectric properties of many halide semiconductor materials are presented. Important material properties that are responsible for good carrier transport and high resistivity in detector materials are identified. Defect migration and related polarization phenomenon are also discussed.

9213-38, Session 9

Thin-film-based scintillators for hard x-ray microimaging detectors: the ScinTAX Project

Alexander Rack, ESRF - The European Synchrotron (France); Angelica Cecilia, Karlsruher Institut für Technologie (Germany); Paul-Antoine Douissard, ESRF - The European Synchrotron (France); Klaus Dupre, Volker Wesemann, FEE GmbH (Germany); Tilo Baumbach, Karlsruher Institut für Technologie (Germany); Maurice Couchaud, CEA-LETI (France); Xavier Rochet, OPTIQUE PETER (France); Heinrich Riesemeier, Bundesanstalt für Materialforschung und -prüfung (Germany); Thierry Martin, ESRF - The European Synchrotron (France)

The project SCINTAX aimed at developing novel thin scintillating films for the application in high performance X-ray imaging and subsequent to introduce new X-ray detectors to the market. To achieve this aim lutetium orthosilicate (LSO) scintillators doped with different activators were grown successfully by liquid phase epitaxy. The LSO high density (7.4 g/cm3) the effective atomic number (65.2) and the high light yield make this scintillator highly applicable for indirect X-ray detection in which the ionising radiation is converted into visible light and then counted by a digital detector. A modular indirect detection system has been developed to fully exploit the potential of this thin film scintillator for 2D and 3D imaging. The system is compatible for high-resolution imaging with moderate dose as well as adaptable to intense high-dose applications where radiation hard microimaging detectors are required. The presentation will outline the achieved performances and technical details on this high-resolution detector system which is now available. Selected example applications demonstrate the great potential of our optimised detector system for hard X-ray microimaging, i.e. either to improve image contrast due to the availability of efficient thin crystal films or to reduce the dose to the sample.

9213-39, Session 9

Oxidation/reduction reactions at the metal contact-TlBr interface: an x-ray photoelectron spectroscopy study

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TlBr radiation detector operation degrades with time and is thought to be due to electromigration of Tl and Br vacancies within the crystal as well as the metal contacts migrating into the TlBr crystal itself due to electrochemical reactions at the metal/TlBr interface. X-ray photoemission spectroscopy (XPS) was used to investigate the metal contact surface/interfacial structure on TlBr devices. Device-grade TlBr was polished and subjected to a 32% HCl etch to remove surface damage prior to Mo or Pt contact deposition. High-resolution photoemission measurements on the Tl 4f, Br 3d, Cl 2p, Mo 3d and Pt 4f core lines were used to evaluate surface chemistry and non-equilibrium interfacial diffusion. Results indicate that anion substitution at the TlBr surface due to the HCl etch forms TlBr1-xClx with consequent formation of a shallow heterojunction. In addition, a reduction of Tl3+ to Tl1+ is observed at the metal contacts after device operation in both air and N2 at ambient temperature. Understanding contact/device degradation versus operating environment is useful for improving radiation detector performance.

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9213-40, Session 9

Design and development of quaternary semiconductors for radiation detection

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There is a strong need to develop a low cost quaternary semiconductor material based detectors to solve the long standing problem of the high cost and low yield cadmium zinc telluride (CZT) and cooled Ge-based detectors and low resolution of halide radiation detectors. Quaternary semiconductors are good alternatives and can be very efficient.

9213-41, Session 9

Investigation of low-leakage radiation detectors on n-type 4H-SiC epitaxial layers passivated with SiO2 and Si3N4

Khai Nguyen, Sandeep K. Chaudhuri, Krishna C. Mandal, Univ. of South Carolina (United States)

4H-SiC epitaxial Schottky barrier detectors have been demonstrated as low noise, high resolution, high sensitivity, high temperature operation capability, and radiation hard sensors. The surface leakage current can be further reduced by deposition of passivating layers on the epitaxial surface which leads to a further improvement of detector resolution. Thin (~nm) layers of silicon dioxide (SiO_2) or silicon nitride (Si_3N_4) deposited on 4H-SiC epitaxial layers act as excellent passivating layers. In the present study we have fabricated large area (~12 mm^2) Schottky barrier radiation detectors on 20 um thick n-type 4H-SiC epitaxial layers some passivated with SiO_2 and some with Si_3N_4 layers. The passivating layers were deposited using a PECVD unit and characterized using X-ray photoelectron spectroscopy. Schottky barrier junctions were fabricated by depositing thin nickel contacts (~10 nm) on the epilayer using photolithography after etching away a window (area ~12 mm^2) on the passivation layer. The detectors have been characterized through current-voltage (I-V), capacitance-voltage (C-V) and alpha spectroscopic measurements. The results were compared with that of our conventional detectors fabricated without surface passivations.

9213-42, Session 10

Development of an x-ray generator using a pyroelectric crystal for x-ray fluorescence analysis on planetary landing missions

Hiroki Kusano, Yuki Oyama, Masayuki Naito, Hiroshi Nagaoka, Haruyoshi Kuno, Eido Shibamura, Nobuyuki Hasebe, Yoshiharu Amano, Waseda Univ. (Japan); Kyeong J. Kim, Korea Institute of Geoscience & Mineral Resources (Korea, Republic of); José A. Matias Lopes, Univ. de Coimbra (Portugal)

The elemental abundance and its distribution on planetary surface are essential to the planetary science to investigate the origin and evolution of planet. In a landing mission to planetary surface, the X-ray fluorescence analysis is a suitable approach to obtaining the concentration of chemical elements in rocks and soils around the landing site. An active X-ray spectrometer, which consists of a silicon drift detector (SDD) and multiple pyroelectric X-ray generators (PXGs), is now being developed as a payload candidate for a future planetary landing mission. The PXG is composed of a pyroelectric crystal, a temperature controller, and thin metallic target, which are enclosed within a small sealed vessel filled with low pressure gas. In this study, we have investigated the X-ray emission of PXG to develop new one with high and reliable X-ray flux. Also, the low-energy X-ray emission was tested by changing target material in order to enhance the detection efficiency of light major elements. In the experiment, a pyroelectric crystal ($LiTaO_3$) was heated by a Peltier device, and then the emission X-rays from the crystal and Cu or Mo target were measured by an SDD in a vacuum chamber. We found that the X-ray intensity is nearly independent on the ambient gas species, but it is dependent on the ambient gas pressure, crystal temperature, and distance between crystal and target. More than 10^6 cps of the time-averaged X-ray emission rate was observed by optimizing the operation conditions. The current progress on the PXG development will be presented.

9213-43, Session 10

Investigation of low-energy response of a plastic scintillator and its implication on the sensitivity of a hard x-ray focal plane Compton polarimeter

Tanmoy Chattopadhyay, Santosh V. Vadawale, Physical Research Lab. (India)

Polarization measurements of celestial astrophysical sources in X-rays offer opportunity of detailed study of behaviour of matter in extreme gravitational and magnetic field. Hard X-ray polarimetry is specifically useful since at higher energies expected polarization from the sources is higher than that at lower energies.

Compton polarimeters when coupled with hard X-ray optics can provide sensitive polarization measurements in hard X-rays with a broad energy band. An important point for Compton polarimeters is that the sensitivity of the instruments critically depends on the lower energy detection limit of the active scatterer.

The active scatterer mostly comprises of plastic scintillators because of its low atomic number constituents and thus higher Compton scattering efficiency against photoelectric absorption. Therefore, it is important to know the characteristics of plastic scintillators at lower energy depositions in order to have a realistic estimate of the energy range and sensitivity of Compton polarimeters. However, it is difficult to estimate the lower energy threshold of a plastic scintillator with usual spectroscopic methods. In this context, we set up an experiment that involves detection of Compton scattered photons from a thin long plastic scintillator by a high resolution CdTe detector at different scattering angles. We found that detection below 1 keV is quite possible, however, with decreasing probability of detection. We also present a semi-analytical treatment to verify the observed results and therefrom finally estimate the realistic energy range and sensitivity of the Compton polarimeter.

9213-44, Session 10

Xenon detector with high energy resolution for gamma-ray line emission registration

Alexander S. Novikov, Sergey E. Ulin, Irina V. Chernysheva, Valery V. Dmitrenko, Victor M. Grachev, Denis V. Petrenko, Alexander E. Shustov, Ziyaetdin M. Uteshev, Konstantin F. Vlasik, National Research Nuclear Univ. MEPhI (Russian Federation)

Description of xenon detector (XD) for gamma-ray line emission registration is presented. The detector provides high energy resolution and is able to operate under extreme environmental conditions (wide temperature range and unfavorable acoustic action). Resistance to acoustic noise as well as improvement in energy resolution has been achieved by means of real-time digital pulse processing. Another important XD feature is the ionization chamber's thin wall with composite housing, which significantly decreases the mass of the device and expands its energy range especially at low energies.

Xenon detector can be widely used for different fundamental and applied tasks such as ecological radiation monitoring, nuclear reactor control, resistance countering nuclear terrorism, radiation customs control, etc. Particularly this device is planned to be used onboard an unmanned aircraft vehicle for ecological monitoring of areas close to atomic industry objects. Furthermore XD is a part of scientific equipment of spacecraft "Interheliozond", which will approach the Sun by spiral trajectory.

9213-45, Session 10

Emergency OSL/TL dosimetry with integrated circuits from mobile phones

Sergii Sholom, Stephen McKeever, Oklahoma State Univ. (United States)

Mobile phones are currently considered as potential emergency dosimeters whereby doses received by the phone's owners during, say, a radiation facility accident or radiological terrorism attack, can be determined. Many components of mobile phones may serve as emergency dosimeters through application of the appropriate dosimetric technique. Most common examples involve the use of ceramic resistors and optically stimulated luminescence (OSL), or glass displays and electron paramagnetic resonance (EPR).

In the present study, integrated circuits (ICs) from mobile phones were tested using both OSL and thermoluminescence. ICs as potential dosimeters have an advantage that they are bulky and can be easy located and extracted from any mobile phone in contrast to resistors which are microsized and have a tendency to be smaller as phone design develops. ICs are also protected from both environmental and phone internal light in contrast to glass displays.

Several tens of ICs extracted from eleven mobile phones (including smartphones) were tested. Both OSL and TL signals were detected after exposure to ionizing radiation doses; the molding compounds of ICs were found to be responsible for the radiation-induced signals. Basic dosimetric characteristics were studied, namely: dose response; minimum measurable doses; and stability of the signals after exposure. Corresponding dose reconstruction protocols were developed.

The main advantage of the OSL technique with ICs is a much higher sensitivity to the radiation exposure while the TL technique demonstrates a better stability of the radiation-induced signals. Both techniques were found to be suitable for dose reconstruction using ICs.

9213-46, Session 10

Use of a position-sensitive multi-anode photomultiplier tube for finding gamma-ray source direction

Sanjoy Mukhopadhyay, Richard J. Maurer, Paul P. Guss, National Security Technologies, LLC (United States)

In an urban environment where gamma-ray background counts vary rapidly, it is important to determine the angle (with respect to the detector system) of a discrete gamma-ray–emitting source for localization purposes. We have recently developed a handheld gamma-ray detection system that provides gamma-ray energy spectral data and angular position of the target source. The handheld detection system uses a sodium-doped cesium iodide (CsI:Na) segmented scintillator assembly consisting of four 1? ? 1? ? 1.5? thick CsI:Na crystals arranged in a 2 ? 2 array. Crystals are packaged in a thin-walled aluminum container with a flange for a hermetically sealed optical/mechanical connection to an H8500 photomultiplier tube (PMT) assembly. The emission maximum of CsI:Na peaks at 420 nm and is well matched to the photocathode sensitivity of a bialkali PMT. The photoelectron yield for gamma-rays amounts to 85% of that of an equivalent NaI:Tl crystal. The decay time of CsI:Na at 630 ns is less than that of CsI:Tl. The Hamamatsu H8500 flat-panel PMT has features particularly suited for this work: it is position-sensitive, extremely compact (12 mm height), and has a 49 ? 49 mm effective area and a minimal peripheral dead zone (mm). The H8500 PMT's metal channel dynode is used for charge multiplication in an 8 ? 8 anode array used for charge collection and position calculation. MCPNX simulation of the sensor performance and measured angular resolution data from small gamma-ray sources are presented for near field measurements (~ 3 meters from the source).

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9214-19, Session PMon

Dual-modality probe for imaging prostate cancer

Yonggang Cui, Brookhaven National Lab. (United States); Terry Lall, Hybridyne Imaging Technologies, Inc. (Canada); Flavien Daloz, Jean Marc Hebrard, GE Healthcare France (France); Ashish Dharnidharka, GE Healthcare (United States); James Ionson, Hybridyne Imaging Technologies, Inc. (Canada); Giuseppe S. Camarda, Anwar Hossain, Utpal Roy, Ge Yang, Ralph B. James, Brookhaven National Lab. (United States)

Advanced development of Cadmium Zinc Telluride (CdZnTe) detectors has motivated its application in medical imaging. Over the past few years, we successfully developed a compact trans-rectal gamma camera (ProxiScan™) using CdZnTe detectors to image prostate cancer. Recently, we improved the technology by developing a bi-modality imaging probe, which combines the ProxiScan™ gamma camera with ultrasound imaging. The new device enables co-registration of functional and anatomical images, allowing physicians to pin-point the tumors within the prostate gland with higher precision. In this presentation, we will discuss the design of the new imaging probe and show preliminary test results.

9214-1, Session 1

Dual-energy computed tomography system using a high-speed photon counter

Eiichi Sato, Yasuyuki Oda, Satoshi Yamaguchi, Iwate Medical Univ. (Japan); Osahiko Hagiwara, Hiroshi Matsukiyo, Akihiro Osawa, Toshiyuki Enomoto, Manabu Watanabe, Shinya Kusachi, Toho Univ. (Japan)

To develop a dual-energy X-ray CT system, we have performed investigation of high-speed dual-energy photon counting using two comparators and a zero-dark-counting YAP(Ce)-MPPC detector. To measure X-ray spectra, the photocurrent from the MPPC is amplified by a high-speed current-voltage amplifier, and the event pulses are sent to a multichannel analyzer (MCA). The MPPC was driven in pre-Geiger mode at an MPPC bias voltage of 70.7 V. Successively, the event pulses are sent to two high-speed comparators for selecting two minimum photon energies to perform dual-energy CT. Photon-counting computed tomography (PC-CT) is accomplished by repeated linear scans and rotations of the object, and two sets of projection curves of the object are obtained simultaneously by the linear scan. The image granulation is improved using two frequency-voltage converters with integrators. Using this dual energy CT, two different-energy tomograms are obtained simultaneously, and energy subtraction imaging has been carried out.

9214-2, Session 1

Developments of metal artifact reduction methods of cone-beam computed tomography

Kun-Long Shih, National Taipei Univ. of Technology (Taiwan); Jyh-Cheng Chen, National Yang-Ming Univ. (Taiwan)

While clinical applications of cone-beam Computed Tomography (CBCT) have expanded, current CBCT technology has limitations due to the streak artifacts caused by metallic objects. The aim of this work was to develop an efficient and accurate metal data interpolation in sinogram domain to achieve artifact suppression and to improve CT image quality which can reduce the streak artifacts and improve the diagnostic value of the CBCT images of vertical root fractures.

We designed three physical phantoms to synthesize teeth with metal post insertion and vertical root fracture. The metal artifacts reduction methods by manipulating projection data were developed. Metal object segmentation in raw data and replacement of the segmented region by new values using three interpolation methods, (1) Simple replcement - to replace the raw data of metal object by the simple threshold value, (2) Half Reducing - to reduce the raw data of metal object to half of the value which is over threshold value, (3) Inpainting - to replace the raw data of metal by using the inpainting method. Our references are the CBCT images of the phantoms without the metal implants. The performance was evaluated by comparing the differences of root mean square error (RMSE) and before and after metal artifact reductions. The analytical and iterative reconstruction are used in this research.

All the metal artifacts were reduced effectively. Metal artifacts reduction using method (1) had the best performance in reducing streak artifacts, which improve the differences of RMSE more than 15%. It needs further study when these methods are applied on teeth with fine vertical root fractures. This study indicates that metal artifacts can be reduced effectively by manipulating projection data. Performance of different methods can be evaluated based on objective data provided by the dental phantom model.

9214-3, Session 1

Si-strip detectors for breast imaging *(Invited Paper)*

William C. Barber, DxRay, Inc. (United States); Jan C. Wessel, Nail Malakhov, Interon AS (Norway); Neal E. Hartsough, DxRay, Inc. (United States); Einar Nygard, Interon AS (Norway); Jan S. Iwanczyk, DxRay, Inc. (United States)

We report on the development of silicon (Si) strip detectors for energy-resolved clinical breast imaging. Typically, x-ray integrating detectors based on scintillating cesium iodide CsI(Tl) or amorphous selenium (a-Se) are used in most commercial systems. Recently, mammography instrumentation has been introduced based on photon counting silicon Si strip detectors. Mammography requires high flux from the x-ray generator, therefore, in order to achieve energy resolved single photon counting, a high output count rate (OCR) for the detector must be achieved at the required spatial resolution and across the required dynamic range for the application. The required performance in terms of the OCR, spatial resolution, and dynamic range must be obtained with sufficient field of view (FOV) for the application thus requiring the tiling of pixel arrays and scanning techniques. Room temperature Si strip detector, operating as direct conversion x-ray sensors, can provide the required speed when connected to application specific integrated circuits (ASICs) operating at fast peaking times with multiple fixed thresholds per pixel, provided that the sensors are designed for rapid signal formation across the x-ray energy ranges of the application at the required energy and spatial resolutions. We present our methods and results from the optimization of prototype detectors based on edge illuminated Si strip structures. We describe the detector optimization and the development of ASIC readout electronics that provide the required spatial resolution, low noise, high count rate capabilities and minimal power consumption.

1. W.C. Barber, N. E. Hartsough, and Jan S. Iwanczyk, are with DxRay Inc., Northridge, CA 91324 USA.

2. J. C. Wessel, N. Malakov. and E. Nygard are with Interon AS, Asker, Norway.

9214-4, Session 1

Low-dark-counting high-speed x-ray photon detection using an LSO Crystal and a small photomultiplier tube

Satoshi Yamaguchi, Eiichi Sato, Yasuyuki Oda, Ryuji Nakamura, Hirobumi Oikawa, Tomonori Yabuushi, Hisanori Ariga, Shigeru Ehara, Iwate Medical Univ. (Japan)

To disperse the X-ray photon energy with high count rates, we performed low-dark-counting high-speed photon detection. X-ray photons are detected using a Lu2(SiO4)O (LSO) single-crystal scintillator with a decay time of 40 ns and a small-sized photomultiplier tube (SPMT). The negative output pulse from the SPMT is amplified by an inverse high-speed amplifier, and the event pulses are sent to a multichannel analyzer to measure X-ray spectra. The dark count rate of the SPMT was 0 cps, and gamma-photons from the LSO crystal were detected without an X-ray source. We also carried out photon-counting computed tomography using contrast media with a maximum rate of approximately 1 Mcps and confirmed the energy-dispersive effect with changes in the description voltage of event pulses using a high-speed comparator.

9214-5, Session 2

Alpha-particle liver imaging and microdosimetry with the iQID camera *(Invited Paper)*

Brian W. Miller, Pacific Northwest National Lab. (United States) and College of Optical Sciences, The Univ. of Arizona (United States); Georg Otto, Stefanie Pektor, Christoph Brochhausen, Matthias Miederer, Johannes Gutenberg Univ. Mainz (Germany)

No Abstract Available

9214-6, Session 2

Detailed characterization of small pixel CZT detectors using hybrid pixel-waveform readout for gamma-ray imaging applications *(Invited Paper)*

Ling-Jian Meng, Jon George, Univ. of Illinois at Urbana-Champaign (United States); Yonggang Cui, Aleksey E. Bolotnikov, Giuseppe S. Camarda, Anwar Hossain, Utpal Roy, Ge Yang, Ralph B. James, Brookhaven National Lab. (United States)

The objective of this research effort is to characterize and evaluate small-pixel Cadmium Zinc Telluride (CZT) and Cadmium Telluride (CdTe) detectors, with a hybrid pixel waveform (HPWF) readout system, for gamma ray imaging applications. This effort includes the use the synchrotron X-ray source and other advanced diagnosis techniques at Brookhaven National Laboratory to study the charge collection behavior around small anode pixels and the non-uniform detector response, and analyze the distribution of such defects. We will also report on the energy resolution and 3-D position resolution attainable with the hybrid pixel-waveform readout scheme. Finally, we will present the imaging capabilities of HPWF detectors.

9214-7, Session 2

Fabrication of the pinhole aperture for AdaptiSPECT

Cecile Chaix, The Univ. of Arizona (United States); Matthew A. Kupinski, College of Optical Sciences, The Univ. of Arizona (United States) and Ctr. for Gamma-Ray Imaging (United States); Lars R. Furenlid, The Univ. of Arizona (United States)

No Abstract Available

9214-8, Session 2

TlBr detectors for medical applications *(Invited Paper)*

Hadong Kim, Len Cirignano, Alireza Kargar, Alexei V. Churilov, Guido Ciampi, Yaroslav Ogorodnik, Suyoung Kim, Kanai S. Shah, Radiation Monitoring Devices, Inc. (United States)

No Abstract Available

9214-9, Session 3

Advances in scintillators for medical imaging applications *(Invited Paper)*

Edgar van Loef, Kanai S. Shah, Radiation Monitoring Devices, Inc. (United States)

Scintillators are a key component of the radiation detection systems used in medical imaging applications. In recent years, tremendous progress has been made in the discovery and development of new scintillation materials. Examples include Ce3+ -doped rare earth halides,[1] elpasolites,[2], [3] and garnets,[4] as well as Eu2+ -doped alkaline earth halides.[5], [6] Many of these inorganic scintillators combine the best scintillation properties into one material such as a high light yield, very good energy resolution and excellent proportionality.

For instance, gamma-ray energy resolutions below 3% (FWHM) at 662 keV and excellent non-proportionality of less than 2% (?L) have been achieved with LaBr3:Ce and SrI2:Eu making these two halides strong candidates for SPECT applications, while high density ceramic garnets such as Gd3Al5O12:Ce and Lu3Al5O12:Ce provide a low-cost alternative to inorganic single crystals used for PET.

In this presentation, some of the most promising inorganic scintillator for medical imaging applications will be discussed and developing trends will be highlighted. The progress of large volume crystal growth and the fabrication of ceramic scintillators will be presented.

9214-10, Session 3

High-efficiency microcolumnar LuI3:Ce for high-frame-rate hard x-ray imaging *(Invited Paper)*

Zsolt Marton, Stuart R. Miller, Elena Ovechkina, Charles Brecher, Harish B. Bhandari, Radiation Monitoring Devices, Inc. (United States); Peter Kenesei, Stephen K. Ross, Jonathan Almer, Argonne National Lab. (United States); Bipin K. Singh, Vivek V. Nagarkar, Radiation Monitoring Devices, Inc. (United States)

No Abstract Available

9214-11, Session 3

Nuclear, optical, and magnetic resonance imaging in a mouse mammary window chamber model

Hui Min Leung, College of Optical Sciences, The Univ. of Arizona (United States); Rachel Schafer, Arthur F. Gmitro, The Univ. of Arizona (United States)

No Abstract Available

9214-12, Session 3

Thick CsI(TI) column scintillator for iQID detector and FASTSPECT III system

Ling Han, The Univ. of Arizona (United States); Harrison H. Barrett, College of Optical Sciences, The Univ. of Arizona (United States); H. Bradford Barber, The Univ. of Arizona (United States); Brian W. Miller, Pacific Northwest National Lab. (United States); Lars R. Furenlid, The Univ. of Arizona (United States)

No Abstract Available

9214-13, Session 4

Adaptive SPECT imaging with crossed-slit apertures *(Invited Paper)*

Heather L. Durko, Harrison H. Barrett, College of Optical Sciences, The Univ. of Arizona (United States) and Ctr. for Gamma-Ray Imaging (United States); Lars R. Furenlid, The Univ. of Arizona (United States)

No Abstract Available

9214-14, Session 4

Innovative visualization and segmentation approaches for telemedicine *(Invited Paper)*

Dung C. Nguyen, Janet M. Roveda, Hans N. Roehrig, Marisa H. Borders M.D., Kimberly A. Fitzpatrick M.D., The Univ. of Arizona (United States)

In health care field, we can obtain, manage and communicate high-quality large volumetric image data by computer integrated devices, to support medical care. In this paper we propose several promising methods that could assist physicians in processing, observing and communicating the image data. An innovative segmentation approach, designed for semi-automated segmentation of radiological image, such as CT, MRI, is proposed in this paper to get the organ or interested area from the image. This approach takes advantage of the region-based method and boundary-based methods. Three steps compose the approach: the first step gets coarse segmentation by fuzzy affinity and generates homogeneity operator; the second step divides the image by Voronoi Diagram and reclassifies the regions by the operator to refine segmentation from the previous step; the third step handles vague boundary by level set model.

9214-15, Session 4

A SPECT system simulator built on the SolidWorksTM 3D design package

Xin Li, The Univ. of Arizona (United States) and Ctr. for Gamma-Ray Imaging (United States); Lars R. Furenlid, The Univ. of Arizona (United States)

No Abstract Available

9214-16, Session 4

Preclinical planar imager using a fine-pitch multi-bore collimator and an IQID detector

David S. Fastje, H. Bradford Barber, The Univ. of Arizona (United States); Brian W. Miller, Pacific Northwest National Lab. (United States); Lars R. Furenlid, Ling Han, Zhonglin Liu, The Univ. of Arizona (United States); Harrison H. Barrett, College of Optical Sciences, The Univ. of Arizona (United States) and Ctr. for Gamma-Ray Imaging (United States)

No Abstract Available

9214-17, Session 4

Medical imaging in the teaching world

Hans N. Roehrig, The Univ. of Arizona (United States)

No Abstract Available

9214-18, Session 4

Color calibration techniques

Hans N. Roehrig, Fahad Hashmi, The Univ. of Arizona (United States)

No Abstract Available

9215-15, Session PMon

Real-time acquisition and preprocessing system of transient electromagnetic data based on LabVIEW

Huinan Zhao, Shuang Zhang, Lingjia Gu, Jian Sun, Jilin Univ. (China)

Transient electromagnetic method (TEM) is regarded as an everlasting issue for geological exploration. It is widely used in many research fields, such as mineral exploration, hydrogeology survey, engineering exploration and unexploded ordnance detection. The traditional measurement systems are often based on ARM?DSP or FPGA, which have not real-time display, data preprocessing and data playback functions. In order to overcome the defects, a real-time data acquisition and preprocessing system based on Labview virtual instrument development platform is proposed in the paper, and a calibration model is established for TEM system based on a conductivity loop. The test results demonstrated that the system can complete real-time data acquisition and system calibration. For Transmit-Loop-Receive (TLR) responses, the correlation coefficient between the measured results and the theoretical results is 0.987. The measured results are consistent with the theoretical results. Through the late inversion process for TLR, the signal of underground conductor can be obtained. Due to complex environment, abnormal values exist in the measured data. In order to solve this problem, the judgment and revision algorithm of abnormal signal is proposed in the paper. The test results proved that the proposed algorithm can effectively eliminate serious disturbance signals from the measured transient electromagnetic data.

9215-16, Session PMon

Radoptic effect in InP and GaN for ultrafast scintillator applications

Kristina K. Brown, National Security Technologies, LLC (United States); Paul T. Steele, Lawrence Livermore National Lab. (United States); Alden H. Curtis, National Security Technologies, LLC (United States)

Despite extensive research on new scintillator materials, the essential mechanism of energy absorption, excitation, and photoemission has remained unchanged for over 50 years. Recently, a new class of semiconductor detector that changes its refractive index when subjected to radiation (called the radoptic effect), has been developed and shows promise for applications that need to resolve ultrafast phenomena. Our project investigated the suitability of four such semiconductors for use as high-speed radiation-sensing devices. The materials were thinned, polished, and optically excited in a Fabry-Perot configuration. While index shifts were observed in the indium phosphide samples at incident energy densities of 8.5 ?J/mm2, the gallium nitride samples, at approximately 1 ?J/mm2, were deemed inadequate to our purpose.

9215-17, Session PMon

Characterization of large area silicon drift detectors

Shanmugam Munuswamy, Santosh V. Vadawale, Yashwant B. Acharya, Arpit Patel, Shiv Kumar Goyal, Tanmoy Chattopadhyay, Physical Research Lab. (India)

Silicon Drift Detectors (SDD) are variant of the standard Si-PIN detectors, but having multiple electrodes arrange to generate electric field which guides the electrons towards very small anode. The small geometric area of the charge collecting anode results in very low detector capacitance which in turn provides the typical characteristics of SDD of high energy resolution and capability handle very large count rate. The concept of drift detectors has been known for almost three decades and such detector with typical detector area of as large as ~150 mm2, have become available commercially during last few years. We are developing a discrete array of such large area SDD to design a high resolution X-ray spectrometer with even mode detection and total detector area of 50 – 100 cm2 for the future planetary science or astronomy experiments. In this context, we have carried out detailed characterization of multiple large area SDDs. Here we present the details of our experimental setup and characterization results of 8 large area SDD modules.

The large area SDDs with total area of 109 mm2 with 450 micron thickness procured from KETEK, GmbH. These are available in the form of integrated modules consisting of SDD, JFET, charge integrating capacitor (feedback capacitor), reset diode, temperature sensor (thermister/diode) and Peltier cooler. We have developed a complete single processing chain for SDDs which provides energy resolution of ~150 eV at 5.9 keV for the pulse peaking time of 3 µs and detector temperature of -50°C. The degradation of energy resolution of the SDD based X-ray spectrometer beyond Fano-limit comes mainly from two factors namely, the detector leakage current and the electronics noise associated with the signal readout electronics. We attempted to measure both the components independently to estimate their relative contribution in the degradation of energy resolution. We employed a novel method to measure the leakage current of SDD by measuring the reset frequency of the reset-type CSPA. We find that the leakage current for all eight large area SDDs varies from ~0.9 nA at 20°C to ~1 pA at -50°C and the resulting Equivalent Noise Charge (ENC) of the spectrometer system varies from 42 e -RMS at -8°C to 13 e -RMS at -50°C. The detailed experimental setup and the characterization results will be presented in the conference.

9215-1, Session 1

A new pad-based neutron detector for stereo coded aperture thermal neutron imaging *(Invited Paper)*

Istvan Dioszegi, Bo Yu, Graham Smith, Neil Schaknowski, Jack Fried, Peter E. Vanier, Cynthia Salwen, Brookhaven National Lab. (United States); Leon Forman, Ion Focus Technology, Inc. (United States)

A new coded aperture thermal neutron imager system is being developed at Brookhaven National Laboratory. The camera utilizes a position-sensitive 3He-filled ionization chamber, in which an anode plane is composed of an array of pads with independent acquisition channels. The charge is collected on each of the individual 5x5 mm2 anode pads, (48x48 in total, corresponding to 24x24 cm2 sensitive area) and read out by application specific integrated circuits (ASICs). The new design has several advantages for coded-aperture imaging applications in the field, compared to the previous generation of wire-grid based neutron detectors. Among these are its rugged design, lighter weight and use of non-flammable stopping gas. The pad-based readout occurs in parallel circuits, making it capable of high count rates, and also suitable to perform data analysis and imaging on an event-by-event basis. The spatial resolution of the detector can be better than the pixel size by using a charge sharing algorithm. In this paper we will report on the development and performance of the new pad-based neutron camera, describe a charge sharing algorithm to achieve sub-pixel spatial resolution and present the first stereoscopic coded aperture images of thermalized neutron sources using the new coded aperture thermal neutron imager system.

9215-2, Session 1

Recent results with a combined gamma-ray and neutron imaging detector *(Invited Paper)*

Lakshmi Soundara-Pandian, Chad M. Whitney, Erik B. Johnson, Robert Vinci, Jarek Glodo, James F. Christian, Michael R. Squillante, Radiation Monitoring Devices, Inc. (United States)

Numerous instruments have been developed for performing gamma-ray imaging and neutron imaging for research, non-destructive testing, medicine and national security. However, none are capable of imaging gamma-rays and neutrons simultaneously while also discriminating gamma-rays from the neutron. This paper will describe recent experimental results obtained using a gamma/neutron camera based on CLYC, (Cs2LiYCl6:Ce) scintillation crystals, which can discriminate gamma-rays from neutrons. The ability to do this while also having good energy resolution provides a powerful capability for detecting and identifying shielded special nuclear materials for security applications.

9215-3, Session 1

Rapid response radiation sensors for homeland security applications

Sanjoy Mukhopadhyay, Richard J. Maurer, Paul P. Guss, National Security Technologies, LLC (United States)

The Remote Sensing Laboratory is developing rapid response radiation detection systems for homeland security field applications. The intelligence-driven system is deployed only when non-radiological information about the target is verifiable. The survey area is often limited, so the detection range is small; in most cases covering a distance of 10 meters or less suffices. Definitive response is required in no more than 3 seconds and should minimize false negative alarms, but can err on the side of positive false alarms. The detection system is rapidly reconfigurable in terms of size, shape, and outer appearance; it is a plug-and-play system. Multiple radiation detection components (viz., two or more sodium iodide scintillators) are used to independently "over-determine" the existence of the threat object. Rapid response electronic dose rate meters are also included in the equipment suite. Carefully studied threat signatures are the basis of the decision making. The use of Rad-Detect predictive modeling provides information on the nature of the threat object. Rad-Detect provides accurate dose rate from heavily shielded large sources (like the ones lost in Mexico). Whenever possible sub-second data acquisition will be attempted, and, when deployed, the system will be characterized for false alarm rates. Although the radiation detection materials selected are fast (viz., faster scintillators), their speed is secondary to sensitivity, which is of primary importance. Results from these efforts will be discussed and demonstrated.

This work was done by National Security Technologies, LLC, under Contract No. DE-AC52-06NA25946 with the U.S. Department of Energy and supported by the Site-Directed Research and Development Program.

9215-4, Session 1

Scintillation properties of a Cs2LiLa(Br6)90%(Cl6)10%:Ce3+ (CLLBC) crystal *(Invited Paper)*

Paul P. Guss, Thomas G. Stampahar, Sanjoy Mukhopadhyay, National Security Technologies, LLC (United States); Alexander Barzilov, Amber Guckes, Univ. of Nevada, Las Vegas (United States)

In investigations of Ce3+-doped Cs2LiLa(Br6)90%(Cl6)10% (CLLBC) Elpasolite crystals, the crystals show an excellent neutron and gamma (n/gamma) radiation response. The results of our studies on the scintillation properties of CLLBC viz. radioluminescence, energy resolution, light yield, decay times, and nonproportionality are discussed. The CLLBC detector can provide energy resolution as good as 4.1% at 662 keV (FWHM), which is better than that of NaI:Tl. Because the crystal contains 6Li, CLLBC can also detect thermal neutrons. In the energy spectra, the full energy thermal neutron peak appears near or above 3 MeV gamma equivalent energy. This high-energy signature for the thermal neutron peak means that very effective pulse height discrimination is possible. Unfortunately, because the core-to-valence luminescence observed in other Elpasolites that can be exploited for effective pulse shape discrimination (PSD) is not observed in the CLLBC, other strategies for obtaining the PSD of CLLBC are needed. The n/gamma discrimination capability of CLLBC detectors may be optimized by tuning the cerium doping content for maximum effect on n/gamma pulse shape differences. The value of adding a chlorine component to the nominal CLLB crystal is discussed. Because the crystal contains chlorine, its sensitivity to fast neutrons is better than that of Cs2LiLaBr6 (CLLB). Further, an array of three of these CLLBC detectors may be able to perform directional detection in both the neutron and gamma channels simultaneously.

9215-5, Session 2

Fast hybrid and monolithic CMOS imagers in multi-frame radiography *(Invited Paper)*

Kris K. Kwiatkowski, Fesseha Mariam, Frank Merrill, Chris L. Morris, Paul Nedrow, Alexander Saunders, Los Alamos National Lab. (United States); Vincent Douence, Yibin Bai, Teledyne Imaging Sensors (United States)

We will present the first performance data of a new hybrid Si-sensor/CMOS-ROIC 10-frame burst mode fast imager. The essential part of the hybrid is a large, 44?44 mm^2 imaging area, stitched CMOS chip of 1100?1100 pixel count, with a minimum shutter speed of 50ns.

Performance parameters and examples of data acquired with an older 3-frame 0.5-Mpixel hybrid imager will also be reviewed. The 3-frame imager has been used for several years, in a variety of static and dynamic experiments at the 800MeV proton radiography (pRAD) facility at LANSCE. The seven cameras can operate at inter-frame time of ~250ns to 2s. They can also be operated in a slower "video mode." In that mode the cameras are externally synchronized to 0.1-to-5Hz, 50 ns wide proton beam pulses from the LANSCE accelerator, and record radiographic movies of 10-to-30 minute duration. The performance of the global electronic shutter will be discussed and compared to that of a high-resolution commercial front-illuminated monolithic CMOS imager.

9215-6, Session 2

Proton and neutron radiation hardness of GaN optoelectronic devices *(Invited Paper)*

Ke-Xun Sun, Univ. of Nevada, Las Vegas (United States)

GaN is a wide band gap semiconductor material that has been increasingly used as for electronics devices, and affords promising prospects for radiation hard, integrated radiation detectors. Radiation hardness of the detector and instruments is a critical issue for high flux radiation measurement. Since 2005, we conducted a series of experiments to investigate radiation hardness of GaN devices. We have demonstrated the exceptional proton radiation hardness of GaN/AlGaN optoelectronics devices UV LED, and UV photodiodes, up to fluence level 3E12 protons/cm2. More interestingly we have observed a plateau, where the proton radiation effects ease accruing. In November 2013, we have further conducted neutron radiation hardness tests of GaN devices at Los Alamos Neutron Science Center [1]. Using AlGaN UV LEDs and UV photodiodes as test samples, we systematically measured the I-V curves in real time during neutron irradiation. Up to neutron fluence 3E11 n/cm2, the device PN junction functions are maintained. Similar to proton experiment, the IV curve variations approached saturation when neutron fluence accumulates. These experiments firmly established GaN devices as a promising candidate of the next generation detectors operable in

high radiation flux, such as in high energy density physics experiments. This presentation will give an overview, and discuss future research direction.

[1] K.-X. Sun et al, "Neutron Radiation Hardness of GaN Devices: LANSCE Experiment," Invited paper at Workshop on Frontiers in Electronics," December 17-20, San Juan, Puerto Rico.

9215-7, Session 2

Determining x-ray spectra of radiographic sources with a Compton spectrometer

Amanda E Gehring, Michelle A Espy, Todd J. Haines, James F Hunter, Nick S.P. King, Los Alamos National Lab. (United States); Manuel J Manard, National Security Technologies, LLC (United States); Frank E Merrill, George L Morgan, Robert Sedillo, Los Alamos National Lab. (United States); Rusty Trainham, National Security Technologies, LLC (United States); Algis V Urbaitis, Petr Volegov, Los Alamos National Lab. (United States)

Flash radiography is a diagnostic with many physics applications, and the characterization of the energy spectra of such sources is of interest. A Compton spectrometer has been proposed to conduct these measurements. Our Compton spectrometer is a 300 kg neodymium-iron magnet constructed by Morgan et al [1], and is designed to measure spectra in the <1 MeV to 20 MeV range. In this device, the x-rays from a radiographic source are collimated into a narrow beam that is directed on a converter foil. The forward-selected Compton electrons that are ejected from the foil enter the magnetic field region of the spectrometer. The electrons are imaged on a focal plane, with their position determined as a function of their energy. The x-ray spectrum is then reconstructed. Challenges in obtaining these measurements will be discussed, and include limited dose of x-rays and the short pulse duration (about 50 ns) for time-resolved measurements. I will present energy calibration measurements spectrometer using a Co-60 source and a Bremsstrahlung x-ray source. A preliminary reconstruction of the Bremsstrahlung spectrum will also be included. Considerations for implementation at other radiographic facilities will be discussed.

[1] Morgan et al., Nucl. Instr. And Meth. A308 (1991) 544

9215-8, Session 3

Irregular large-scale computed tomography on graphics processors improves energy-efficiency metrics for industrial applications *(Invited Paper)*

Edward S. Jimenez Jr., Eric L. Goodman, Sandia National Labs. (United States); Ryeojin Park, College of Optical Sciences, The Univ. of Arizona (United States); Laurel J. Orr, Kyle R. Thompson, Sandia National Labs. (United States)

This paper will investigate energy-efficiency for various real-world industrial computed-tomography reconstruction algorithms, both CPU- and GPU-based implementations. We show that the energy required for a given reconstruction is based on performance and problem size. There are many ways to describe performance and energy efficiency for various high-performance computing applications, thus we will investigate multiple metrics including performance-per-watt, energy-delay product, and energy consumption. We found that irregular GPU-based approaches realized tremendous savings in energyconsumption when compared to CPU implementations while also significantly improving the performance-per-watt and energy-delay product metrics. Additional energy savings and other metric improvement was realized on the GPU-based reconstructions by improving storage I/O by implementing a parallel MIMD-like modularization of the compute and I/O tasks. Optimizing software implementation allows for Non-Destructive Facilities to increase processing capacity while minimizing energy requirements. Implementing efficient hardware and software also has the added benefit of reducing facilities operating cost. We will present results for two test datasets; the first is a 64 gigavoxel reconstruction from 1,800 16 megapixel projections and a large dataset that consists of a teravoxel reconstruction from 10,000 100 megapixel projections. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energys National Nuclear Security Administration under contract DEAC04- 94AL85000.

9215-9, Session 3

A high-performance GPU-based forward-projection model for computed tomography applications

Ismael Perez, Edward S. Jimenez Jr., Kyle R. Thompson, Sandia National Labs. (United States)

No Abstract Available

9215-10, Session 3

Fisher information as a gamma-ray detector design tool

Esen Salcin, Lars R. Furenlid, College of Optical Sciences, The Univ. of Arizona (United States) and Ctr. for Gamma-Ray Imaging (United States)

No Abstract Available

9215-11, Session 3

Exploring mediated reality to approximate x-ray attenuation coefficients from radiographs

Edward S. Jimenez Jr., Kyle R. Thompson, Laurel J. Orr, Megan L Morgan, Sandia National Labs. (United States)

No Abstract Available

9215-12, Session 4

X-ray detectors for the Dynamic Compression Sector at the Advanced Photon Source *(Invited Paper)*

Yuxin Wang, Dynamic Compression Sector, Institute for Shock Physics, Washington State Univ. (United States); Stefan J. Turneaure, Institute for Shock Physics, Washington State Univ. (United States); Timothy J. Graber, Dynamic Compression Sector, Institute for Shock Physics, Washington State Univ. (United States); Kurt Zimmerman, Yogendra M. Gupta, Institute for Shock Physics, Washington State Univ. (United States)

The Dynamic Compression Sector (DCS) is a new facility being developed at the Advanced Photon Source with the goal of offering general users a unique capability to examine shock compressed condensed matter in real-time with time resolution between 10 and 150 nanoseconds. A common type of experiment at DCS will be plate impact X-ray diffraction that requires detectors with single x-ray photon sensitivity and near 100% quantum efficiency for 8-35 keV x-ray energies, 2048?2048 pixels with 100?100 ?m2 or larger pixel size,

dynamic range of 104 X-rays per pixel, frame rates up to 100 MHz, and on chip storage for multiple frames. Concurrent radiography imaging measurements with sub-micron resolution and similar efficiency, frame rate, and dynamic range are also desired. Several different detectors are currently being developed for diffraction and high-resolution imaging measurements. We will discuss the range of experiments to be performed at DCS and detector development plans in the next 2-10 year time frame.

9215-13, Session 4

The effect of guard-ring on leakage current and spectroscopic performance of TlBr planar detectors *(Invited Paper)*

Alireza Kargar, Hadong Kim, Len Cirignano, Kanai S. Shah, Radiation Monitoring Devices, Inc. (United States)

No Abstract Available

9215-14, Session 4

Deep-pixel scintillator arrays for high-energy gamma-ray imaging

H. Bradford Barber, David S. Fastje, Lars R. Furenlid, College of Optical Sciences, The Univ. of Arizona (United States) and Ctr. for Gamma-Ray Imaging (United States); Daniel A. Lemieux, Gary P. Grim, Los Alamos National Lab. (United States); Ling Han, College of Optical Sciences, The Univ. of Arizona (United States) and Ctr. for Gamma-Ray Imaging (United States); Brian W. Miller, Pacific Northwest National Lab. (United States); Philip Parkhurst, Proteus, Inc. (United States)

No Abstract Available

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9216-1, Session 1

Impact of LED irradiance on plant photosynthesis and action spectrum *(Invited Paper)*

Most Tahera Naznin, Mark Lefsrud, Michael Schwalb, McGill Univ. (Canada)

The photosynthetically active radiation (PAR) curve represents the percent of light absorbed and utilized by the different pigments in the plant as a function of wavelengths between 400 and 700 nm. High power light emitting diodes (LEDs) are an emerging versatile artificial light source offering many advantages over conventional artificial light sources, including high energy efficiency, long life, and especially the possibility to test out the effects of many different spectral combinations of wavelengths on plant growth and development. This could eventually allow determination of the ideal light emission spectrum for optimal plant growth, allowing for lighting system designs tailored to optimize plant growth while minimizing associated energy costs.

The objective of this study is to determine the impact of the photosynthetic rate of two species of plants to different wavelengths of LEDs. We analyzed the photosynthesis rate verse LEDs at different wavelengths. Two species of plants (lettuce and petunia) were tested under 14 specific wavelengths of LED covering the PAR spectrum. The plants were tested at an irradiance level of 30, 60 and 120 μmol m-2 sec-1 to determine the photosynthetically active radiation (PAR) curve for each species. From our research we found photosynthesis, absorbance, quantum yield and action spectrum peaks in the range of 417 to 450 nm and in the range from 630 to 680 nm. This research will facilitate the improved selection of LEDs in the PAR spectrum.

9216-2, Session 1

Depth compensation in fluorescence molecular tomography using an adaptive support driven reweighted L1-minimization algorithm

Junwei Shi, Fei Liu, Jianwen Luo, Jing Bai, Tsinghua Univ. (China)

In fluorescence molecular tomography (FMT), the distribution of fluorochrome is reconstructed from the diffuse-light measurements obtained from the rotating source–detector pairs placed on the boundary of the medium. Owing to the attenuation of light intensity when it propagates through tissues, the sensitivity of measurements deteriorates quickly with increased depth. Thus the inconsistent contrast in reconstructing fluorescent targets located at different depths is a major challenge in FMT. An adaptive support driven reweighted L1-minimization (ASDR-L1) algorithm is proposed here for depth compensation in FMT. ASDR-L1 is a modification of the restarted L1 regularization-based nonlinear conjugate gradient (re-L1-NCG) algorithm previously proposed by our laboratory (Shi. et al. Optics Letter, 2013). In ASDR-L1, the sequence of L1-minimization subproblems are replaced by a sequence of weighted L1-minimization subproblems with updated weights applied to the adaptive support estimate. The adaptive support estimate benefits from the restarted strategy in re-L1-NCG and is updated in each iteration. The weights used for the next iteration are computed from the current solution. In the support estimate, different weights are equivalent to different regularized parameters. As an L1-regularized algorithm, a large regularized parameter in ASDR-L1 makes the results concentrate on a small number of big values, whereas a small regularized parameter tends to make the values be evenly distributed. Thus depth compensation in FMT is achieved through iteratively updated weights. Simulation experiments are conducted to confirm the usefulness of ASDR-L1. Through ASDR-L1, the contrast between two identical fluorophores located at different depths is improved from 1:0.56 to 1:0.98.

9216-3, Session 1

Multispectral image restoration of historical documents based on mathematical morphology

Juan Carlos Valdiviezo-Navarro, Edwin Lechuga-Salem, Univ. Politécnica de Tulancingo (Mexico); Gonzalo Urcid, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

The restoration of historical documents is the main problem that experts have faced during the last years given that much of this cultural heritage is damaged for different reasons. Multispectral and hyperspectral imaging have shown to be effective to retrieve useful information concerning the damaged areas in palimpsests and other documents. This research paper introduces an automatic algorithm designed for the virtual restoration of the damaged parts in historical documents. The technique makes use of a multispectral imaging system to acquire a data set in the wavelength interval from 400 to 900 nm, which is used for further restoration. Hence, assuming the presence of linearly mixed spectral pixels registered from this multispectral set, the approach here discussed is based on morphological n-dimensional operations to extract the constituent materials spectra (endmembers) that are able to separate such mixtures. Each endmember can be used to solve a constrained linear equation in order to produce a fractional abundance map indicating the proportions of the corresponding material. The obtained abundance maps are then used to locate cracks and holes in the document under study; thus, once we have located these areas, the restoration process is performed by the application of a region filling algorithm, based on morphological dilation, to reconstruct each one of the damaged parts. The last step of the procedure consists in color interpolation to restore the original appearance of the filled areas in the document. This procedure has been applied to a multispectral data set collected from a Mexican pre-Hispanic codex belonging to the XI Century, from which restoration results are presented.

9216-4, Session 1

Oxygen saturation detection aided with the theory of lock-in amplifier

Manjin Liu, Mei Hui, Ming Liu, Yuejin Zhao, Liquan Dong, Hong Wu, Xiaohua Liu, Lei Yang, Zhu Zhao, Yun Feng, Di Chen, Beijing Institute of Technology (China)

This paper proposes a method with the theory of lock-in amplifier to recover the pulse signal and calculate the oxygen saturation. The pulse signal is obtained based on the method of PhotoPlethysmoGraphy (PPG). We use a LED as the light source and a photoelectric diode as the receiver to get a measured pulse wave. Because the pulse wave obtained by this method is easily disturbed by motion artifact, we use an electrocardiogram (ECG) signal to aid PPG measurement . Firstly, the ECG signal is processed by the wavelet transform and get the heart rate. Secondly, with the value of heart rate, a typical noise free pulse waveform can be constructed. Finally, we use it as a reference signal to get a recovered pulse wave by the theory of lock-in amplifier. In essence, a lock-in amplifier takes the measured pulse signal, multiplies it by the reference pulse signal, and integrates it over a specified short time. The resulting signal is a DC pulse signal which we need, where the component from any signal that is not at the same frequency as the reference signal is attenuated close to zero. The out-of-phase component of the signal that has the same frequency as the reference signal is also attenuated. Thus, the value of oxygen saturation can be calculated accurately through two pulse waveforms of red(660nm) and infrared(940nm) light. Some volunteers were tested, the correlation coefficient between the experimental data and the data provided by a

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reference instrument is 0.98, proving that this method has high reliability and utility.

9216-65, Session 1

Multifunction medical endoscope system with optical fiber temperature sensor

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Thermal therapy (e.g. RF treatment, RF ablation, microwave cutting etc.) is one of the effective operations for tumor treating and curing. Since tumor tissues are more susceptible to heat than normal tissues, in thermal therapy operations, temperature is a crucial parameter. As the temperature is too low, the tumor tissues cannot be killed; otherwise, the temperature is too high, the operation may damage the normal tissues around tumors. During thermal therapy operation, the heating power is normally supplied by high-frequency EM field, so traditional temperature sensors, such as thermal couples, thermistors, cannot work stably due to EM interference. We present a multi-function endoscope optical fiber temperature sensor system. With this sensor setup based on principle of fluorescence life time, the temperature on operation point is detected in real time. Furthermore, a build-in endoscope centered in the fiber sensor, so the operation field can be viewed or imaged at the same time in clinic operation. This design can navigate the operation, particularly for in vivo operations. In the sensor system, the temperature sensor measurement range 30°C-150°C, the resolution achieve 0.3°C, and the imaging fiber buddle contains more than 50k fibers. As the sensor probe is very thin (less than 2mm in diameter), it can be assembled in the RF operation knife. With the presented sensor system in clinic operation physicians can check the temperature in the operation point and view the operation point at the same time.

9216-5, Session 2

A roadmap to global illumination in 3D scenes: solutions for GPU object recognition applications

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The study of the interaction of light with matter in 3D space is of significant complexity. This phenomenon, known as global illumination, it is widely investigated by many researchers in the computer vision and graphics community. Global illumination is given by a mathematical model that describes interaction between light and matter in 3D space with respect to an observer. Global illumination plays a key role in many computer vision algorithms because it can be used to describe the appearance of objects in an observed scene captured from a specific observation point. In the state-of-the-art of the field there are several models to describe global illumination. The digital solution of global illumination models is given by a rendering equation whose digital implementation possesses high computational complexity. As a result, modern algorithms for solving efficiently the rendering equation are required. In this work we present a detailed review of the most successful global illumination models as well as the existing algorithms for solving the rendering equation. We present a performance comparison of the most successful global illumination algorithms implemented for different physical environments. The tested illumination algorithms are implemented in a graphics processing units (GPU) whereas the performance of the tested algorithms is given in terms of realism and computational complexity.

9216-6, Session 2

Illumination adaptation with rapid-response color sensors

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In traditional vision systems, high-level information is usually inferred from images or videos captured by cameras, or depth images captured by depth sensors. These images, whether gray-level, RGB, or depth, have a 2D structure which describes the spatial distribution of the scene. Although surveillance video cameras have widely been used for automatic monitoring of indoor spaces, one major concern on this technique is the privacy of subjects. Staying in a monitored room simply makes people feel uncomfortable. In this paper, we explore the possibility to use a distributed arrangement of color sensors to infer high-level information, such as room occupancy. A color sensor can be a very cheap photodiode, and each color sensor can be thought of as a single pixel with no spatial information. Unlike a camera, the output of a color sensor has only a few variables. However, if the lights in the room are color controllable, we can use the outputs of multiple color sensors under different lighting conditions to recover the light transport model (LTM) in the room. While the room occupancy changes, the LTM also changes accordingly, and we can use machine learning to establish the mapping from LTM to room occupancy. We have set up a smart lighting room with twelve color-tunable LED lights and multi-channel color sensors as our testbed. We collected LED input and sensor output data under different occupancy conditions. We have achieved high accuracy using support vector machine (SVM) to classify fifteen occupancy categories. Such an occupancy determination technique will help us to build a privacy-preserving occupancy-sensitive intelligent illumination system.

9216-7, Session 2

Multiple-samples-method enabling high dynamic range imaging for high frame rate CMOS image sensor by FPGA and co-processor

Blake C. Jacquot, Nathan G. Johnson-Williams, The Aerospace Corp. (United States)

CMOS imagers are replacing CCDs to become the dominant visible image sensor for space-based applications. However, in a variety of space imaging applications, CMOS imagers often have a smaller dynamic range that precludes their direct replacement for CCDs. This issue can be partly resolved through techniques and algorithms for High/Wide Dynamic Range CMOS (HDR/WDR CMOS). Though the algorithmic HDR approaches are used in some high-volume commercial CMOS imager applications, these techniques have not yet been widely deployed or optimized for space systems.

Implementing real-time algorithms that enable high dynamic range operation (or other image processing methods such as change detection) requires significant computing power. The system must capture, analyze, and store every pixel according to the constraints of the algorithm without dropping frames. In the acquisition system, the task is often split between the FPGA or ASIC front-end and the microprocessors backend.

We present results from a prototype camera system that implements a real-time Multiple Sampled Pixel Level algorithm (aka, "Last Sample Before Saturation") to create an HDR imager in real time. The system is built around a commercial 1280 x 1024 CMOS image sensor with 10-bits per pixel and up to 500 Hz frame rate with a peak data rate above 7.5 Gbps. We analyze statistical and imagery data collected at room temperature for SNR versus photocurrent, among other figures of merit. The results conform to expectations of a model that uses only dark current, read noise, and photocurrent as input parameters.

9216-8, Session 2

Optical design and characterization of an advanced computational imaging system (ACIS)

R. Hamilton Shepard III, Christy Fernandez-Cull, MIT Lincoln Lab. (United States); Boxin Shi, Christopher Barsi, Ramesh Raskar, MIT Media Lab. (United States)

We have developed an advanced computational imaging system (ACIS) that couples an optical architecture accommodating both image and pupil plane coding with an MIT Lincoln Laboratory (LL) computational imaging array capable of advanced on-chip processing. We present the optical design and characterization of ACIS, which is capable of simultaneous dynamic pupil and image plane coding. The flexible optical architecture couples either a digital micromirror device (DMD) for amplitude modulation or a deformable mirror (DM) for dynamic phase coding at a pupil plane. ACIS optical requirements are meant to leverage two LL detectors: an Orthogonal Transfer (OT) CCD capable of on-chip global sub-pixel charge shifting for spatial super-resolution and a digital readout integrated circuit (DROIC) with advanced per-pixel capabilities for novel temporal sampling and on-chip data processing. This paper discusses the derivation of optical component requirements, optical design metrics, and performance analysis for ACIS.

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9216-9, Session 3

Image analysis algorithms for the advanced radiographic capability (ARC) grating tilt sensor at the National Ignition Facility

Randy S. Roberts, Erlan S. Bliss, Michael C. Rushford, John M. Halpin, Abdul A. S. Awwal, Richard R. Leach Jr., Lawrence Livermore National Lab. (United States)

The Advance Radiographic Capability (ARC) at the National Ignition Facility (NIF) is a laser system designed to produce a sequence of short pulses used to backlight imploding fuel capsules. Laser pulses from a short-pulse oscillator are dispersed in wavelength into long, low-power pulses, injected in the NIF main laser for amplification, and then compressed into high-power pulses before being directed into the NIF target chamber. In the target chamber, the laser pulses hit targets which produce x-rays used to backlight imploding fuel capsules. Compression of the ARC laser pulses is accomplished with a set of precision-surveyed optical gratings mounted inside of vacuum vessels. The tilt of each grating is monitored by a measurement system consisting of a laser diode, camera and cross hair, all mounted in a pedestal outside of the vacuum vessel, and a mirror mounted on the back of a grating inside the vacuum vessel. The cross-hair is mounted in front of the camera, and a diffraction pattern is formed when illuminated with the laser diode beam reflected from the mirror. This diffraction pattern contains information related to relative movements between the grating and the pedestal. Image analysis algorithms have been developed to determine the relative movements between the gratings and pedestal. In the paper we elaborate on features in the diffraction pattern, and describe the image analysis algorithms used to monitor grating tilt changes. Experimental results are provided which indicate the high degree of sensitivity provided by the tilt sensor and image analysis algorithms.

9216-10, Session 3

Autonomous pedestrian localization technique using CMOS camera sensors

Chanwoo Chun, Monroe Community College (United States)

The user localization problem is important, and has a wide variety of applications such as navigation, crime prevention and security. In the case of cellular wireless communication, the most elementary method of localizing a mobile station is to identify the basestation (or the access point (AP) for indoor environment) that currently serves the mobile. Further accuracy can be attained by measuring the received signal strengths (RSSs) from multiple basestations, as well. However, the most accurate localization for a mobile station or vehicle is using the global positioning system (GPS). Major limitation of these techniques is that they are not autonomous, but need infrastructure. Furthermore, GPS-based methods cannot be used for indoor mobile localization. Autonomous navigation is possible using an inertial measurement unit (IMU) for aerial vehicles. However, an IMU cannot be used with a slowly moving pedestrian.

In this paper we present a pedestrian localization technique that does not need infrastructure. The proposed angle-only measurement method needs specially manufactured shoes. Each shoe has two CMOS cameras and two LEDs attached at the inward side. The line of sight (LOS) angles towards the two LEDs on the moving shoe are measured using the two cameras on the other fixed shoe. More specifically, the proposed technique alternately finds the LOS angles of the moving shoe with respect to the fixed one, utilizing the fact that one of the two feet is always fixed on the ground when we walk. Then the desired position and orientation of a shoe can be derived from the four angle measurements. In principle, Hansel and Gretel could use the proposed method rather than a trail of bread crumbs to find their way back home.

The error accumulation is a major disadvantage of any kind of autonomous or dead reckoning methods, and therefore frequent calibration is needed. According to our simulation, the proposed technique accumulates small amount of error in the along-track direction, but relatively large amount in cross-track. However, this cross-track error does not cause much problem if the proposed technique is used as a map-assisted navigation device. Our simulation results shows that a pedestrian walking down in a shopping mall wearing this device can be accurately guided to the front of a destination store located 100m away, if the floor plan of the mall is available.

9216-11, Session 3

Digital vision sensor for collision avoidance and navigation

Joseph H. Lin, MIT Lincoln Lab. (United States)

Autonomous vehicles, particularly unmanned air vehicles (UAVs), are playing an increasingly prominent role in military and civilian applications. Small UAVs (0.25 – 2 m wingspan) capable of safely operating at low altitudes in close proximity to structures and terrain offer exciting new opportunities. Critical to the success of these small UAVs is the ability to sense and react to their environment, specifically to detect and avoid obstacles. MIT Lincoln Laboratory is developing a unique image sensor and new UAV flight-control algorithms to fill this capability gap.

We describe the architecture of the image sensor, which integrates silicon Geiger-mode avalanche photodiodes with custom designed readout integrated circuitry. High-frame rate images (~1000fps) feed into on-chip data processing circuits that compute apparent velocities of objects in the scene (optical flow). Combined with the UAV's velocity, these apparent velocities provide a coarse depth map that can be used for collision avoidance and local navigation. This is similar to early visual processing that birds and insects use to fly through cluttered environments.

The optical flow algorithm is derived from the classic Horn and Schunck algorithm. This algorithm assumes that scene reflectance remains constant from frame to frame, thus image motion can be computed from spatio-temporal gradients. The large linear system of equations

that results is typically solved using an iterative method such as Gauss-Seidel. However, we unroll this iteration over multiple frames taking advantage of the high frame rate of our imager. Due to the high frame rate, pixel velocities do not exceed 1 pixel/frame thus the optical flow is continually updated from successive frames. We show MATLAB results using simulated and real images that compare the accuracy of this algorithm with other popular optical flow algorithms such as the Lucas and Kanade algorithm.

The APD detectors are fabricated in MIT Lincoln Laboratory's micro-electronics fabrication facility and the readout electronics and optical flow circuitry will be fabricated in a 90nm standard CMOS process. We plan to tape out the read-out chip by the end of this year.

9216-12, Session 3

Detecting objects with partial obstruction at the ARC split beam injector images at the National Ignition Facility

Abdul A. S. Awwal, Richard R. Leach Jr., Randy S. Roberts, Karl Wilhelmsen, David McGuigan, Jeffrey A. Jarboe, Lawrence Livermore National Lab. (United States)

The National Ignition Facility (NIF) utilizes 192 beams, four of which are diverted to create the Advanced Radiographic Capability (ARC) by generating a sequence of short laser pulses. This backlighted beam after being converted to X-ray will create a radiographic movie and provide an unprecedented insight into the imploding dynamics and serve as a diagnostic for tuning the experimental parameters to achieve fusion. One such beam is the centering beam of the pre-amplifier module which due to a split path obstructs the central square alignment fiducials. This fiducial is used for alignment and also as reference for PSS system. Image processing algorithms are used to process the images and calculate the position of various fiducials in the beam path. We discuss the algorithm to process ARC split beam injector (SBI) centering images with partial fiducial information.

9216-13, Session 4

GPU implementation of wave field translation method for fast hologram generation

Seok Lee, Hocheon Wey, Dongkyung Nam, Dusik Park, Samsung Advanced Institute of Technology (Korea, Republic of)

Hologram Pattern generation complexity is proportional to the number of input object points and SLM resolution. To enlarge viewing angle of holographic display (>30 deg.), small pixel size around 1 um is required. If we assume that the display size is 50 inches as usual TV in consumer market, we need hologram pattern over 1 tera pixels. Thus fast holographic pattern generation is essential problem in commercialization of holographic display which is considered as ideal 3D display. In previous work of authors, 2 step wave field projection method was proposed to overcome accumulation problem of point source based method. In the first step, 2D projection of wave field for 3D object is calculated by radial symmetric interpolation (RSI) method to the predefined reference depth, and then in step 2 it is translated toward depth direction using Fresnel transformation. In this paper, we proposed parallel processing method of 2 step wave field projection method using GPU. We used CUDA and NVIDIA GPUs such as GT 530, GTX 580, GTX 780. To accelerate RSI method in step 1, the object points are divided into small groups and processed in each CUDA cores in parallel. In step 2, FFT is performed using cuFFT library, and also multiplication of transfer function is processed in parallel. The effectiveness of method is proved by computer simulation and optical experiment. Experimental results show that proposed method is 5901 times faster than analytic method, and 344 times faster than RSI method for the 1 million object points and full HD SLM resolution.

9216-14, Session 4

Morlet Wavelet transformed holograms for numerical adaptive view-based reconstruction

Kartik Viswanathan, Patrick Gioia, Orange SA (France); Luce Morin, Institut National des Sciences Appliquées de Rennes (France)

We use an improved Gabor wavelet design to compress holograms. Using the good time-frequency localization properties of the Gabor wavelet, we perform a pruning of the wavelet coefficients based on the position of the viewer. We describe an optical setup for the reconstruction of such holograms whilst providing a comparison with numerical reconstruction. We show that a view-dependent compression technique is more a efficient method for hologram compression.

9216-15, Session 4

Averaged Stokes polarimetry applied to characterize parallel-aligned liquid crystal on silicon displays

Andrés Márquez, Francisco J. Martínez, Sergi Gallego, Manuel Ortuño, Jorge Francés, Augusto Beléndez, Inmaculada Pascual, Univ. de Alicante (Spain)

Parallel-aligned liquid crystal on silicon (PA-LCoS) displays have become the most attractive spatial light modulator device for a wide range of applications, due to their superior resolution and light efficiency, added to their phase-only capability. Proper characterization of their linear retardance and phase flicker instabilities is a must to obtain an enhanced application of PA-LCoS. We present a novel polarimetric method, based on Stokes polarimetry, we have recently proposed for the measurement of the linear retardance in the presence of phase fluctuations. This can be applied to electrooptic devices behaving as variable linear retarders, and specifically to PA-LCoS. The method is based on an extended Mueller matrix model for the linear retarder containing the time-averaged effects of the instabilities. We show experimental results which validate the predictive capability of the method. The calibrated retardance and phase fluctuation values can then be used to estimate the performance of the PA-LCoS device in applications, such as in diffractive optics. Some results will be given.

9216-16, Session 4

Adaptive SLM-based compensation of intermodal interference in few-mode optical fibers

Vladimir S. Lyubopytov, Valeriy K. Bagmanov, Albert K. Sultanov, Ufa State Aviation Technical Univ. (Russian Federation)

Area of applications involving optical beams with phase front vorticity, carrying orbital angular momentum, is known to be broadened steadily. However, transmission of such waves through relevant distances in optical fibers poses a problem of random mode coupling. In the paper we propose a method for compensation of interference between LP-modes, propagating through optical fiber. Because of coherent nature of the laser source, producing few-mode radiation, matrix propagation model with complex mode coupling coefficients is used to define the transmission medium. Since mode coupling phenomena is caused by the fiber index profile deviations and mechanical deformation, and propagation matrix of the fiber is known to be time-dependent, modal decomposition for probe signal with interferometric diffractive optical element (DOE) is applied to distinguish actual complex coefficients straightforwardly. Then inverse propagation matrix is calculated. To implement appropriate optical-

domain modal filtering, reconfigurable multibranch DOE matched with particular modes is considered. Then such an element may be encoded as phase-only hologram by means of SLM. With this approach modes can be separated spatially in the compensating DOE's far field and handled independently with corresponding coefficients.

In the paper physical bases of modes propagation in step-index optical fiber firstly are described, including such effects as intermodal interference, differential group delay and mode-dependent loss. Then the issue is considered from positions of the system theory. Based on joint consideration of these approaches, transmission functions for analyzing and compensating DOEs are expressed. Finally, efficiency of the method for intermodal interference mitigation is confirmed by computer simulation results.

9216-17, Session 4

3D extended NPDD model of holographic grating formation in photopolymer materials

Haoyu Li, Yue Qi, John T. Sheridan, Univ. College Dublin (Ireland)

When the large thickness is used as the holographic storage materials, a non-ignorable problem is the light intensity attenuation in depth due to high absorptive of the dye. For this reason more completely modeling the evolutions inside the material is necessary to consider into the developed standard kinetic model. In this paper the photo-polymerization processes during the large thickness holographic grating formation are analyzed. A 3-dimensional algorithm is present by deriving the system partial differential rate equations governing each associated chemical species, and using the finite difference approximation, these equations can be solved numerically. This extended model describes the time varying behaviors of the non-uniform photo-physical and the photochemical evolutions in photopolymer materials. In this model both dye molecules consumption and light energy absorption are calculated time varyingly, and then the polymer and monomer concentrations distributions are obtained. Applying the Lorenz-Lorenz relationship, the non-uniform grating formatted in material depth, and its refractive index, which is distorted from ideal sinusoidal spatial distribution, can be more accurately predicted.

9216-38, Session PMon

A new light intensity controllable measurement matrix based on compressed sensing *(Invited Paper)*

Jiayan Zhuang, Nanjing Univ. of Science and Technology (China)

In the optical system based on compressed sensing, when the modulated light is too strong, the detection will be in the nonlinear region of the photo-detector which will make the measurement data nonlinear. The nonlinear measurement will certainly decrease the image reconstruction quality. In this paper, we will propose a new measurement matrix which will deal with the above problem instead of the conventional Gaussian matrix. The proposed measurement matrix can control the intensity of the modulated light, which will make the detection be in the linear region to have a linear measurement data. The theoretical analysis and the simulation results show that when the modulated light is too strong to make the measurement data nonlinear, the new measurement matrix can solve the problem and improve the image reconstruction quality of the optical system based on compressed sensing .

9216-39, Session PMon

Interference coloring effects of polymer dispersed liquid crystals

Andriy L. Nehrych, Peter P. Maksimyak, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

Investigations, where the interference principle of spectrum forming was used, have been performed in optical schemes based on Michelson and Fabry – Perot interferometers as well as near singular points.

Investigations of spectral transmittance were mainly performed for liquid crystal monolayers. Depending on the applied voltage, in the optical scheme with crossed polarizers, the colour of polychromatic radiation that has passed through liquid crystals is formed. Polymer dispersed liquid crystals (PDLC) can also be used as an object, which performs the spectral selection of polychromatic radiation depending on the applied voltage. But the nature of this phenomenon is different.

In this paper we have investigated the interference mechanism of forming of the spectrum which passes through the PDLC. For this, we have considered an experimental model of polychromatic light passing through PDLC, spatial-frequency filtering radiation by PDLC and the transmission of radiation by PDLC depending on the applied voltage.

We have studied the effects of colouring of the composite “liquid crystal – polymer matrix”. The sample of such composite permits us to study the effects of interference colouring as a function of path difference between the beams passing through polymer and liquid crystal as well as a function of the intensity ratio of such beams. Changing the path difference of the interfering beams was achieved by changing a voltage applied to the PDLC.

9216-40, Session PMon

Monocular pose estimation algorithm based on the bundle adjustment method

Weimin Li, Yan Li, Univ. of Science and Technology of China (China); Lichun Zhu, National Astronomical Observatories (China); Di Zhang, Hui Liu, Yu Zhao, Univ. of Science and Technology of China (China)

This paper propose the attitude measurement method of the target with single camera based on bundle adjustment method. Firstly, the intrinsic parameters and extrinsic parameters of the single camera is calibrated with the non-control points on the measurement target; Secondly, the image coordinates of the feature points on the measurement target are acquired by the single camera; Thirdly, the attitude of the target is calculated with the bundle adjustment method. The experiment results show that the method can get high precision with its rotation angles error within 20 arc-second and its translation error within 20 micron.

9216-41, Session PMon

The spatial stochastization of optical radiation scattered by liquid crystal in the process of phase transition

Mykhailo S. Gavrylyak, Peter P. Maksimyak, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

This paper represents the investigation results of spatial chaotization of optical field scattered by liquid crystals during phase transition liquid – liquid crystal under electric field. It was choosed for this study two stochastic parameters of the field, namely, Lyapunov's maximal index and correlation exponent. It has been established that maximum variances of phase inhomogeneities of the nematic liquid crystal corresponds to maximum fluctuations of order parameter under temperature of phase transition liquid – liquid crystal. Was found that analysis of the radiation field scattered during the phase transition process the liquid-liquid crystal allows to accurately determine the phase transition temperature and voltage of forming Williams's domains.

9216-42, Session PMon

Influence of the photopolymer properties in the fabrication of diffractive optical elements

Sergi Gallego, Roberto Fernández, Andrés Márquez, Francisco J. Martínez, Manuel Ortuño, Stephan Marini, Cristian Neipp, Inmaculada Pascual, Augusto Beléndez, Univ. de Alicante (Spain)

A wide range of chemical compositions are possible to design photopolymers. These materials are also appealing for diffractive and holographic applications due to their capability to modulate the refractive index and/or the thickness when illuminated. Some of the most interesting applications for photopolymers are the optical data storage, security systems, surface relief photo-embossing, diffractive and refractive optical elements, holographic elements, solar concentrators, optical detectors and hybrid optoelectronic 3-D circuitry. Looking for an optimized chemical composition for each application many different photopolymers compositions may be needed enabling a variety of materials properties: materials with low or high rates of monomer diffusion, low or high values of shrinkage, long or short length of polymer chains and low or high light absorption. In parallel many models are presented in order to predict the photopolymers recording and the post exposure evolution. In this work we use one of these experimentally checked models to study the influence of the material characteristics in the final diffractive optical element recorded in the material. We study the changes in the surface relief and in the refractive index in order to understand the importance of each material property in the final diffractive optical element recorded.

9216-43, Session PMon

Mexican sign language recognition using normalized moments and artificial neural networks

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This paper presents a Computer Vision System for Mexican Sign Language Recognition (MSL) using Normalized Moments and Artificial Neural Networks; database was recorded using twenty four static signs of MSL alphabet and five versions per sign. A digital camera with CMOS sensor was used for capturing the signs without gloves or color markers, a solid background was selected in order to perform better skin segmentation, original images were gray scale transformed. Forty nine normalized moments were computed from gray scale alphabet signs to feed a Multi-Layer Perceptron in a k-fold cross validation scheme achieving 93.33% of recognition rate.

9216-44, Session PMon

Mueller-matrix processing of biological tissues polarization images and reconstruction of parameters phase and amplitude anisotropy

Olexander V. Dubolazov, Vladimir Ushenko, Artem Karachevtsev, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

Experimental approbation of azimuthally stable Mueller-matrix reconstruction of linear birefringence and dichroism of structured optically anisotropy networks, endometry in differentiation of histological sections of benign (fibromyoma) and malignant(adenocarcinoma) tumors of womb side has been presented.

Employment physically reasoned and analytically defined algorithms of parameters reconstruction of linear birefringence and dichroism of biological crystal networks in differentiation of optical anisotropy changes, constrains with different degree of pathological severity – precancerous(atrophy and polip of endometry) states of cervix of the uterus.

Creation and experimental approbation of “two-wave” method of Mueller-matrix reconstruction of phase and amplitude parameters of polycrystalline films anisotropy of bile and blood plasma for early diagnostics of diabetes and oncological (cancer of breast) diseases.

9216-45, Session PMon

Azimuthally stable laser polarimetry of polycrystalline films of human biological fluids

Vladimir Ushenko, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine); Galina Koval, Bukovinian State Medical Univ. (Ukraine); Maxim Sidor, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

This research presents the results of experimental researches of:

• coordinate distributions of generalized Mueller-matrix elements of optical anisotropy of ordered febrile network (histological sections of skeletal muscle) and polycrystalline film, formed by optically active molecules of bile;

• coordinate maps, histograms and logarithmic dependencies of the power spectra distributions of azimuthally stable Mueller-matrix invariants, characterizing the phase and amplitude anisotropy of the multilayer febrile network (myosin and collagen network fibers) of histological sections of the uterine wall endometrial layer;

• coordinate statistical and scale-self-similar structure of Mueller-matrix invariants of the optically anisotropic layer film, formed with networks of crystalline amino acids and proteins collagen, synovial fluid of the joint man.

9216-46, Session PMon

Numerical reconstruction of digital holograms on free software distribution ImageJ

Jorge Ivan Garcia Sucerquia, Raul Andres Castañeda Quintero, Univ. Nacional de Colombia Sede Medellín (Colombia)

In this honours project we present a plugin capable of performing numerical reconstruction of digital holograms through two methods of reconstruction: Fresnel Transform and angular spectrum. The plugin is called DH_OD which is implemented in the software of public domain ImageJ. This software allows processing, analyzing and editing digital Images. Besides ImageJ also allows creating plugins using the Java TM programming language to generate algorithms that permit digital image processing. DH_OD allows following step by step the process of reconstruction using emergent windows for viewing the recorded hologram its Fourier transform and finally the numerical reconstruction of the hologram. On the reconstructed hologram can be made rigorous analysis with the help of the tools built in ImageJ, edge detection, histograms, filters, brightness, contrast , are some of the operations one can carry out . The importance of the work is that developed plugins are free to use tools for any person who in their research work performs numerical reconstruction of digital holograms.

9216-47, Session PMon

Correlation-optical method for cement particle size definition

Mykhaylo P. Gorsky, Peter P. Maksimyak, Andrew P. Maksimyak, Yuriy Fedkovych Chernivtsi National Univ. (Ukraine)

Article describes optical correlation method of cement particle size

distribution. It is based on transverse coherent function definition. It is shown that set of particles with random form can be substituted with set of spherical particles. This result was obtained by simulation of different particles sets with different forms and orientations. According to this, we developed method of experimental data processing. This method converts transverse coherent function into particle size definition function. Experimental measurements were processed by polarization transverse shearing interferometer. Our method, of data processing, decreases result dependence from interferometer noise, emission source intensity fluctuations and different refractive index values of separate cement particles. Described method is fast and allows getting accurate cement particle distribution by sizes. It can be reused for any similar sets of particles.

9216-48, Session PMon

Effect of rate of change of frequency characteristics of the optical spectral device based on acousto-optic tunable filter

Georgy Korol, St. Petersburg State Univ. of Aerospace Instrumentation (Russian Federation); Dmitry Moskaletz, Saint Petersburg Electrotechnical University (Russian Federation); Oleg Moskaletz, St. Petersburg State Univ. of Aerospace Instrumentation (Russian Federation)

Envelope instantaneous frequency oscillation change rate impact on the optical spectral characteristics of device based on acousto-optic tunable filter is analyzed. Those characteristics are determined by its spectrum spread function, which is the response to a homogeneous plane monochromatic wave. Optical spectral device based on acousto-optic tunable filter are characterized by two temporal characteristics: time of analysis and time of the analyzed range of optical frequencies scan. Spectrum spread function of optical spectral device based on acousto-optic tunable filter with auxiliary linear frequency-modulated signal generally has a complex dependence on the envelope signal instantaneous frequency change rate. Operation mode of the device when envelope oscillation instantaneous frequency change rate exceeds accepted meanings is investigated. Mathematical analysis of envelope oscillation instantaneous frequency change rate impact on characteristics of the optical device based on acousto-optic tunable filter is shown.

The connection between the genuine optical spectrum (spectrum in the mathematical sense) and the spectrum obtained by using the spectral device is determined. This relationship is obtained in the form of linear integral operators for complex energy spectra. Kernels of these operators are, respectively, the power, complex and spectrum spread functions of the spectral device. In this case the result of the analysis of the optical spectra is given in the form of energy correlations because photodetectors in optical range are quadratic.

9216-49, Session PMon

The Stability of color discrimination threshold determined using pseudoisochromatic test plates

Brigita Zutere, Kaiva Jurasevska, Aija Livzane, Univ. of Latvia (Latvia)

Red-green color vision deficiency is one of the most common genetic disorders. A previously printed set of pseudoisochromatic plates (KAMS test, 2013) was created for individual discrimination on threshold determination in case of mild congenital red-green color vision deficiency using neutral colors (colors confused with gray). The diagnostics of color blind subjects was performed with Richmond HRR (4th edition, 2002) test, Oculus HMC anomaloscope, and further the examination was made using the KAMS test. The samples consisted of 4 males between 20 and 24 years old: three of them with deuteranomalia and one with protanomalia.

Due to the design of the plates, the threshold of every sample was defined as the intensity at which the stimulus was detected 75% of the time, so the just-noticeable difference (jnd) was calculated. Authors had performed repeated discrimination threshold measurements (5 times) for all four subjects under controlled illumination conditions. Psychophysical data were taken by sampling an observer's performance on a psychophysical task at a number of different stimulus saturation levels.

It was observed that values of jnd had a tendency to descend over time, and this tendency was not dependent on the color of stimuli in the psychophysical task. Difference between expected and actual protan and deutan values was not significant.

Authors investigate the hypothesis that individual threshold of every repeated discrimination threshold measurement of examined subjects is invariable. It is hoped that this study will stimulate further investigations in this field.

9216-50, Session PMon

Combining two strategies to optimize biometric decisions against spoofing attacks

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Spoof attack by replicating biometric traits represents a real threat to an automatic biometric verification/authentication system. This is because the system, originally designed to distinguish between genuine users from impostors, simply cannot distinguish between a replicated biometric sample (replica) from a live sample. An effective solution is to obtain some measures that can indicate whether or not a biometric trait has been tempered with, e.g., liveness detection measures. These measures are referred to as evidence of spoofing or anti-spoofing measures. In order to make the final accept/rejection decision, a straightforward solution to define two thresholds: one for the anti-spoofing measure, and another for the verification score. This approach has two weaknesses. First, if the anti-spoofing measure has a high classification error rate, this error will adversely increase the overall false rejection rate of the system. Second, setting the two thresholds is a highly empirical exercise. We compared two variants of a method that relies on applying two thresholds -- one to the verification (matching) score and another to the anti-spoofing measure. Our experiments carried out using a signature database as well as by simulation show that both the brute-force and its probabilistic variant turn out to be optimal under different operating conditions.

9216-51, Session PMon

Comparison of methods of suppression of undesired diffraction orders at numerical reconstruction of digital Fresnel holograms

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Digital holography is popular tool in such areas as interferometry, microscopy, information processing. Main information limitation of digital holograms is quantity of pixels of registering cameras. Necessity of spatial separation of informative diffraction order from undesired orders leads to additional reduction of quantity of resolved elements in reconstructed object. Methods of numerical elimination of undesired orders are aimed at overcoming this problem. They are widely used due to processing simplicity. Goal of this work is comparison of different methods of numerical elimination of undesired diffraction orders.

Eight methods of undesired orders suppression were tested: filtering in hologram plane by subtracting: hologram mean value (HM), mean values of hologram pixels groups, values obtained by hologram median filtering (MF); filtering in frequency plane: selection of field of frequencies zeroing

(FZ), automatic threshold filtering (AT), using hologram Laplacian, using Gauss filtering (GF), nonlinear filtering in a single quadrant. Comparison of these methods was performed using computer generated Fresnel holograms with resolution equaled to 512x512. Under numerical testing it was found that good quality of reconstructed images is provided by five methods: FZ, MF, GF, AT, HM. These methods showed roughly similar results between each other. Experiments with recorded digital Fresnel holograms were performed for final comparison.

Digital Fresnel holograms with pixel size 9x9 µm2 and quantity of pixels up to 2048x2048 were recorded and used for further methods comparison. The FZ method showed best results for suppression of undesired diffraction orders. Slightly worse results demonstrated the MF and GF method.

9216-52, Session PMon

Increasing quality of computer generated kinoforms using direct search with random trajectory method

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Method of increase of quality of computer generated kinoforms is proposed. It is simple direct search method similar to direct binary search method for binary holograms generation. Main difference is that proposed direct search with random trajectory (DSRT) method designed to process arrays with multiple phase (or amplitude) levels. Main stages of proposed method described as follows. First, kinoform is generated with conventional method such as Gerchberg-Saxton. Then, elements of kinoform are sequentially switched to obtain lower normalized standard deviation (NSTD) of reconstructed image from desired image. Element processing sequence is random to retain spatial pseudo-randomness. This process goes on until minimum NSTD drop level is reached. Proposed technique was applied to several kinoforms generated with standard Gerchberg-Saxton method. For kinoform with 32 phase levels forming typical image “Lenna” (with 128x128 pixels and 256 gray levels) NSTD from 0.077 dropped to 0.059. Proposed method provides decrease in NSTD compared to original kinoforms up to 29%.

9216-53, Session PMon

Analysis of correlation metrics performance for minimum energy invariant filters

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The article presents results of research of correlation metrics for filters with minimization correlation energy.The recognition problem of grayscale images of object subjected to out-of-plane rotation distortion was considered. The results are given for usage metrics of basic types for variety of recognition problems under different conditions (with background, in presence of noise and etc). Comparison of results shows the best metrics for different cases.

9216-55, Session PMon

Three-dimensional photon counting microscopy using Bayesian estimation

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We present three-dimensional photon counting microscopy using Bayesian estimation. In conventional photon counting imaging, maximum likelihood estimation or Bayesian estimation with uniform prior information has been used. However, their visual quality is not enough to recognize 3D microorganisms when low number of photons is used. Our proposed method uses the nonuniform prior information of microorganisms to estimate 3D profile of them. Therefore, this method may enhance the visual quality of 3D microscopy results with low number of photons.

9216-56, Session PMon

2D moiré fringe of square-aperture planar microlens array

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Moiré fringe has been used widely in many fields, such as precision measurement, lithography alignment, holographic storage and engineering design. In recent years, the main research object of moiré fringe is one-dimensional gratings. With the emergence of square aperture planar microlens array, the development of 2-D Moiré fringe will come into a new stage. Square aperture planar microlens array has higher fill factor and better image, and consists of some square lenses which have identical optical property and are arranged in order. Moreover, square aperture planar microlens array has moiré display effect to the matching micro graphics array. In this paper, based on the theory of moiré fringe caused by one-dimensional gratings, 2-dimension moiré fringe is studied by simulating the overlap between square aperture planar micro lens array and corresponding micro graphics array in different angles. The variety law of the pitch is analyzed and the magnification is discussed. The theoretical results are well agreed with the experimental results. These results not only can be used to explain the dynamic and magnifying display effect of square aperture planar microlens array to micro graphics array, but also enrich the theory of planar micro lens array, broaden its application, and promote the relationship between microlens array and moiré fringe to some extent .

9216-57, Session PMon

Simulation of time-dispersion spectral device with sample spectra accumulation

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This research is conducted in order to design a spectral device for light sources power spectrum analysis. The spectral device should process radiation from sources, direct contact with radiation of which is either impossible or undesirable. Such sources include jet blast of an aircraft, optical radiation in metallurgy and textile industry. In proposed spectral device optical radiation is guided out of unfavorable environment via a piece of optical fiber with high dispersion. It is necessary for analysis to make samples of analyzed radiation as short pulses.

Dispersion properties of such optical fiber cause spectral decomposition of input optical pulses. The faster time of group delay vary the stronger the spectral decomposition effect. This effect allows using optical fiber with high dispersion as a major element of proposed spectral device. Duration of sample must be much shorter than group delay time difference of a dispersive system. In the given frequency range this characteristic has to be linear. The frequency range is 400 … 500 THz for typical optical fiber. Using photonic-crystal fiber gives much wider spectral range for analysis.

In this paper we propose simulation of single pulse transmission through dispersive system with linear dispersion characteristic and quadratic-

detected output responses accumulation. During simulation we propose studying influence of optical fiber dispersion characteristic angle on spectral measurement results. We also consider pulse duration and group delay time difference impact on output pulse shape and duration. Results show the most suitable dispersion characteristic that allow choosing the structure of photonic crystal fiber – major element of time-dispersion spectral analysis method and required number of samples for reliable assessment of measured spectrum.

9216-58, Session PMon

Application of improved genetic algorithm in camera calibration

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In camera calibration, solving the internal parameters can often be converted to solving the overdetermined nonlinear equations. Newton iteration method is often heavily influenced by the initial value, easy to fall into local minimum. In this paper, the improved genetic algorithm is not affected by initial value, but also has good global search capability. This method retains global search ability of the genetic algorithm, and also absorbs the advantages of Newton iterative method with strong local search ability, fast convergence speed, good accuracy and convergence speed.

9216-59, Session PMon

Performance analysis of bi-directional broadband passive optical network using erbium-doped fiber amplifier

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A passive optical network (PON) consists of an optical terminal (OLT) at the service provider's central office and a number of optical network units (ONUs) near end users. A PON reduces the amount of fiber and central office equipment required compared with point-to-point architectures. The broadband PON (BPON) has the ability to support high-speed data, voice, and video services to home and small businesses customers.
In this work, the performance of bi-directional BPON is analyzed for both down and up streams traffic cases by the help of erbium doped fiber amplifier (EDFA). BPON is one of the three types of passive optical network. The other two types of passive optical network are Ethernet PON (E-PON) and Gigabit PON (G-PON). The importance of BPON is reduced cost. Because PBON uses a splitter, which is a passive device, the cost of the maintenance between providers of the service side and the customer side is suitable. In the proposed research, BPON has been tested by the use of bit error rate (BER) analyzer. BER analyzer realizes max. Q factor, minimum bit error rate, and eye height. Passive optical components such as bidirectional circulator, splitter and others have been used in the modeling and simulation. The system has been verified by the use of the Optiwave simulator. The structure of the design has been analyzed according to the data rate, fiber length, extinction ratio, and coding technique. An EDFA has been used when transmitting data along long fiber distances.

9216-60, Session PMon

Analysis of the confluence of three patterns using centering and pointing system (CAPS) images for the advanced radiographic capability (ARC) at the National Ignition Facility

Richard R. Leach Jr., Abdul A. S. Awwal, Erlan S. Bliss, Randy S. Roberts, Michael C. Rushford, Karl Wilhelmsen, Tom Zobrist, Lawrence Livermore National Lab. (United States)

The Advance Radiographic Capability (ARC) at the National Ignition Facility (NIF) is a laser system that employs up to four petawatt (PW) lasers to produce a sequence of short pulses that generate X-rays which backlight high-density internal confinement fusion (ICF) targets. Employing up to eight backlighters, ARC can produce an X-ray "motion picture" to diagnose the compression and ignition of a cryogenic deuterium-tritium target with tens-of-picosecond temporal resolution during the critical phases of an ICF shot. Multiframe, hard-X-ray radiography of imploding NIF capsules is a capability which is critical to the success of NIF's mission. The function of the Centering and Pointing System (CAPS) in ARC is to provide superimposed near-field and far-field images on a common optical path The Images are then analyzed to extract beam centering and pointing data for the control system. The images contain the confluence of pointing, centering, and reference patterns. The patterns may have uneven illumination, particularly when the laser is misaligned. In addition, the simultaneous appearance of three reference patterns may be co-incidental, possibly masking one or more of the patterns. Image analysis algorithms have been developed to determine the centering and pointing position of ARC from these images. In the paper we describe the image analysis algorithms used to detect and identify the centers of these patterns. Results are provided, illustrating how well the process meets system requirements.

9216-61, Session PMon

Pipeline security threat event classification method based on optimized support vector machine

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The way of efficiently classifying the manual digging, machine excavation, vehicle passing and other pipeline security threats, is an imperative problem for optical fiber pipeline security system. To solve this problem, a security threats classification method based on optimized support vector machine is proposed. In this method, the artificial bee colony algorithm is introduced to optimize the penalty factor and kernel parameter of support vector machine, and the classification error is used as the fitness value. After optimization, the support vector machine is used as classifier. Firstly, to testify its effectiveness, the proposed method is tested through the UCI feature datasets with different amount of classes and dimensions, and it is compared with support vector machines optimized by ant colony optimization algorithm, genetic algorithm and particle swarm optimization algorithm. It is testified that the proposed method can achieve higher classification accuracy in all cases and cost less running time when the amount of classes is small. Field test in Gangzao pipeline is also made to testify the performance of the proposed method. The proposed method is used in optical fiber pipeline security system to classify the signals of manual digging, machine excavation and vehicle passing acquired by the optical fiber laying along the pipeline. The wavelet energy of every frequency band is calculated as the features. At last, the proposed method is utilized to classify the features. Comparison is made between the proposed method and support vector machines optimized by other optimization algorithms. It is revealed from the result that, because the exploration and exploitation are both given consideration to in the parameter search process, the proposed method

can achieve higher classification accuracy and cost less running time. Therefore, it is concluded from the experiment result that the proposed method is very effective in pipeline security threat events classification.

9216-62, Session PMon

Modulation transfer function approximation application in imaging systems

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Modulation Transfer Function (MTF) is one of the most important optical performance measures of an imaging system. There are several methods to calculate MTF. In this sense, the number of frames per measurement and the distribution of measurement regions in the image plane should be chosen carefully to fully identify the system performance.

In this study, it is aimed at determining an optimum testing procedure for an imaging system by varying the number of MTF measurements and measurement regions in the image plane. The tests are repeated with different samples in order to prove repeatability of the method proposed. This approach yields a time and effort optimal procedure for testing the selected system prior to its production. Although the study focuses on a selected design, it can be adopted to different optical imaging systems as well.

First of all a point has been selected to capture frames and measure MTF. Then MTF measurements have been calculated from 50 frames taken from this point. The average MTF of these 50 frames are almost equal to the average MTF of 5 frames. Thus, the result is averaging 5 frames is sufficient to get an accurate MTF value for a given point.

In the next section of the study different points on an image plane calculated by the inner field-of-view rings have been selected as measurement points. MTF measurements have been taken from a total of 27 points in the image plane and have also been interpolated in points where measurements have not been taken from 23, 15 and 7 points respectively. As a result, taking measurements from 15 points is sufficient to identify an optical systems overall MTF performance.

9216-63, Session PMon

The separation of 1/f noise of semi-conductor laser based on GPU parallel computing

Haipeng Chen, Jilin Univ. (China) and Univ. of Wisconsin-Madison (United States); Shuxu Guo, Tian Zhang, Jian Sun, Jilin Univ. (China)

1/f noise has been applied as one of the most important index for evaluating the reliability of semiconductor laser . The changing amplitude value of 1/f noise power spectrum density shows the working life of the semiconductor laser,which is also used for doing evaluation for the laser features in different working current, power,junction temperature. this paper proposed a novel scheme for no-touch detection for 1/f noise. we apply the compressed sensing algorithm to separate 1/f noise from the low-frequency combined electronics noise. due to its long time processing for weak signal reconstruction algorithm, in this paper, we apply the high performance computing by using the GPU platform for improved achieving, also keep the precision of algorithm.

9216-64, Session PMon

The method of evaluation for 1/f low-frequency electronics noise based on compressed sensing

Haipeng Chen, Jilin Univ. (China) and Univ. of Wisconsin-Madison (United States); Shuxu Guo, Tian Zhang, Jian Sun, Jilin Univ. (China)

In this paper, we aimed to separate the 1/f noise from the original signal, and analyzed its characteristics of power spectrum. First, an N-level wavelet transform has been applied for the original data signal before the compressed sensing observation for the original signal. Compared with the tradition measurement procession of compressed sensing, the measurement matrix here is replaced with the circulant matrix. This can greatly reduce the measurement number compared with the random Gaussian matrix. In addition, the usage of circulant matrix is also helpful for the reconstruction performance of sparse signal.

9216-18, Session 5

Improvements to vehicular traffic segmentation and classification for real-time emissions estimation using networked traffic surveillance cameras

Jeffrey B. Flora, Mahbubul Alam, Khan M. Iftekharuddin, Old Dominion Univ. (United States)

The goal of this intelligent transportation systems work is to improve the real-time understanding of the impact of carbon emissions caused by vehicular traffic on highway systems. Vehicles are observed and classified by leveraging techniques in computer vision and machine learning using the existing infrastructure of networked traffic surveillance cameras. Using the Motor Vehicle Emissions Simulator (MOVES) application developed by the Environmental Protection Agency (EPA), this vehicle class data may be applied to form a real-time estimation of carbon emissions. A software algorithm is proposed to solve the problems of vehicle segmentation, clustering, and classification in varying cases of traffic density as well as a variety of weather conditions. Vehicles are segmented from the background using an adaptive Gaussian mixture model algorithm. SIFT features are extracted from the vehicles and used to reduce the effects of vehicular occlusion and improve tracking of vehicles through the camera scene. Morphological properties and histogram of oriented gradient (HOG) features are derived from the detected vehicles, and classification is performed using a multi-class support vector machine algorithm. Additionally, single camera calibration techniques are applied to provide vehicle speed estimations and to reduce the dependence on camera angle so that this algorithm may be applied to a broad range of surveillance cameras. Results are evaluated by comparing the vehicle segmentation produced by this algorithm to a manually generated ground truth. Furthermore, the resulting classification scheme proposed in the algorithm gives an average classification rate of 85% under good quality segmentation in initial testing.

9216-19, Session 5

Baseline estimation in flame's spectra by using neural networks and robust statistics

Hugo O. Garces, Luis Arias, Alejandro Rojas, Univ. de Concepción (Chile)

In this work a baseline estimation method based on artificial neural network structure, combining robust statistics with multivariable analysis is proposed. The method automatically discriminate wavelengths ranges belonging to continuous target of a mixed measured flame spectrum with continuous and discontinuous features, surpassing requirements of full-spectrum measurements of baseline target. In this work we analyse mixed flame spectral database, computing Jolliffe statistics from Principal Components Analysis, detecting non-correlated wavelengths associated to baseline behaviour. Thus, the optimal number of neurons in hidden layer based on Akaike's final Prediction Error is obtained, estimating continuous baseline in full-spectral range. The performance of this method was compared to FDM (first-derivative method) achieving better results with proposed method in terms of GFC (goodness-of-fit

coefficients) and RMSE (root-means squared error) metrics values. This method was used to correlate total continuous integrated radiation with the fan speed in an industrial furnace, determining combustion parameters leading in optimum operations conditions which can be used for optimization in early stages.

9216-20, Session 5

Neural network-based person re-identification using color histograms

Alex Kuefler, Occidental College (United States); James DePaola, California State Univ., Fullerton (United States); Thomas T. Lu, Jet Propulsion Lab. (United States)

High traffic public spaces, such as airports and train stations, may use networks of multiple cameras in order to survey different parts of the grounds simultaneously. If a suspicious activity is detected by one camera and the suspect leaves that camera's field of view, there is a need to re-identify that same individual as he or she passes different cameras in the network. We present an automatic target recognition (ATR) algorithm that tracks moving bodies across screen and records the frequency distribution of pixel hues recovered from blob analysis of that figure every frame. The resulting color information is then compressed to 50 components using Independent Component Analysis (ICA) as soon as the figure leaves the screen. The system works in two stages. During the first stage, these compressed color signatures are used for supervised training of an artificial neural network. In the following stage, the neural network classifies tracks as matching the ground truths during real time video. Encouraging experimental results were obtained using test case scenarios filmed for the CAVIAR project. Color histogram based re-identification appears to be an accurate, yet computationally inexpensive technique for use in automated video surveillance. The continuing project will be to test this algorithm on videos featuring larger crowds, variations in lighting and targets whose appearance changes over time.

9216-21, Session 6

Quantum nanophotonic circuits for ultralow-power classical information processing *(Invited Paper)*

Jason S. Pelc, Charles Santori, Ranojoy Bose, Raymond G. Beausoleil, Hewlett-Packard Labs. (United States)

While optical nonlinearities are famously weak, the confinement of light to sub-cubic-wavelength volumes using high-quality-factor photonic nanocavities makes low-power nonlinear optical processes possible. The small footprint of nanocavities combined with the high natural bandwidth of photonic systems holds great promise for future information processing applications. But photonic integration trails electronic integration by several decades, and we are only now beginning to envision what a complex nanophotonic circuit might do. We will discuss technology platforms for ultralow-power integrated nonlinear optics using both III-V and group IV semiconductors. We will also describe quantum optical simulations of large-scale photonic sequential logic circuits using phase-space methods, indicating that reliable performance is possible with a few tens of photons per device.

9216-22, Session 6

Mid-IR nonlinear optics on silicon

Ting Wang, Singapore Univ. of Technology & Design (Singapore)

Silicon based nonlinear photonics has been extensively researched at telecom wavelengths in recent years. However, studies of Kerr nonlinearity in silicon at mid-infrared wavelengths still remain limited. Here, we report the wavelength dependency of third-order nonlinearity in the spectral range from 1.6 µm to 6 µm, as well as multi-photon absorption coefficients in the same range. The third-order nonlinear coefficient n2 was measured with a peak value of 1.65x10-13 cm2/W at a wavelength of 2.1 µm followed by the decay of nonlinear refractive index n2 up to 2.6 µm. Our latest measurements extend the wavelength towards 6 µm, which show a sharp decrement of n2 beyond 2.1 µm and steadily retains above 3 µm. In addition, the analysis of three-photon absorption and four-photon absorption processes are simultaneously performed over the wavelength range from 2.3 µm to 4.4 µm. Furthermore, the effect of multi-photon absorption on nonlinear figure of merit in silicon is discussed in detail.

9216-23, Session 6

Optical chaos synchronization and encrypted communications of VCSEL by direct optical injection

Naohito Hosomi, Wakao Sasaki, Doshisha Univ. (Japan)

In this work, we have proposed electro-optical nonlinear delayed feedback systems (NDFS) using VCSEL for the first time. Its optical output can perform more sensitive chaotic dynamics by varying from threshold to maximum rating with only a few mA. Sensitive dependence on initial conditions can be kept by using VCSELs. Besides, it has been possible to vary chaotic output dynamically by a slight difference of initial value in NDFS. We have proposed a chaos synchronization system using two identical NDFS's. We have performed a chaos synchronization of Master-Slave model with unidirectional link, which has optical isolator between master system and slave system. As a synchronization signal we used the LD optical output of the Master System by injecting a part of the output into the Slave System. Though previously we used an electric injection, this time we realized chaos synchronization by optical injection as a first step to align with optical communication with high communication speed. As a result of experiment, correlation coefficient up to about 0.88 was obtained. By varying delay time and feedback gain, variation of correlation coefficient was obtained as 0.19 at Δt=1ms and, where Δt means the gap of delay time, against only 0.01 at $\Delta\mu$=0.01, where $\Delta\mu$ means the gap of feedback gain. In the previous experiment of chaos synchronization by electrical injection with VCSEL's driving current waveform, variations of correlation coefficient attained only 0.01 in each condition. Consequently we understood that the variations of delay time greatly affected variations of correlation in the case of optical injection in comparison with the case of electric injection. We demonstrated application of encrypted communications bearing these consequences. We could utilize these parameters as the secret encryption key, when performing the encrypted communications, since variations of parameters affect correlation. In other words, we suppose, that in communications it will be possible to perform encrypted communications with chaos synchronization when the parameters of NDFSs between transfer and receiver are agreed with each other.

9216-300, Session Plen

Data-adaptive filtering and the state of the art in image processing

Peyman Milanfar, Univ. of California, Santa Cruz (United States)

The most effective recent approaches to processing and restoration of images and video are ones that flexibly adapt themselves to the content of these signals. These high performance methods have come about through the convergence of several powerful ideas from different science and engineering disciplines. Examples include Moving Least Square (from computer graphics), the Bilateral Filter and Anisotropic Diffusion (from computer vision), Boosting and Spectral Methods (from Machine Learning), Non-local Means and Bregman Iterations (from Applied Math), Kernel Regression and Iterative Scaling (from Statistics). These approaches are deeply connected; and in this talk, I will present a framework for understanding many common underpinnings of these

ideas. This has led us to new insights and algorithms, yielding both deeper theoretical analysis, and state of the art results in practice.

9216-24, Session 7

First principles investigation of magnetic noise sources for superconducting qubits on α-Al_2O_3 *(Invited Paper)*

Donghwa Lee, Jonathan DuBois, Vincenzo Lordi, Lawrence Livermore National Lab. (United States)

Ever since the development of novel quantum computing algorithms, the promise of a general purpose quantum computer has attracted both scientists and engineers to the practical problem of realizing such a device. Superconducting qubits (SQs) represent a promising route to achieving a scalable quantum computer. However, the coupling between electro-dynamic qubits and (as yet largely unidentified) ambient parasitic noise sources has so far limited the functionality of current SQs by limiting coherence times of the quantum states below a practical threshold for measurement and manipulation. Further improvement can be enabled by a detailed understanding of the various noise sources afflicting SQs. Sapphire (α-Al2O3) is commonly used as a substrate for SQs and in this study we have investigated the magnetic stability of its surface by using first principles calculations. Both intrinsic and extrinsic surface defects are investigated to identify a plausible microscopic origin of magnetic noise arising from the substrate. Our study shows that various environmental chemical species and adsorbates can introduce paramagnetic noise into the SQs. The fundamental understanding of this important physical origin of quantum decoherence presents an opportunity to develop unique fabrication techniques and designs for minimizing noise. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

9216-25, Session 7

Information encryption, transmission, and retrieval via chaotic modulation in a hybrid acousto-optic Bragg cell under profiled beam illumination

Monish R. Chatterjee, Fares S. Almehmadi, Univ. of Dayton (United States)

Recently, the propagation of a profiled optical beam through an open-loop acousto-optic Bragg cell was examined using a transfer function formalism based on the angular spectra. The results have shown dependence on the effective “Q” (Klein-Cook parameter), the acoustic wavelength and the profile width. Oddly, under large Q (greater than 50) conditions, the output profile begins to deviate from the uniform beam response. For high values of the optical phase shift, the scattered output undergoes an axial shift which is more pronounced for beams with asymmetry or without a central maximum and alternating positive and negative scattered profiles. The device was also studied under closed-loop via intensity feedback, and shown to exhibit more extended chaotic band responses, thereby potentially increasing the dynamic range and parameter sensitivities of the device and any applied signals. The closed-loop was simulated via storing the (open-loop) output scattered amplitudes and thereafter running the time-dynamical quadratic map equation numerically through iterations involving standard nonlinear dynamics, bifurcation maps and Lyapunov exponents. In this paper, we apply simple low- to mid-RF signals (periodic waveforms and low BW audio for example) through the acoustic path which then propagate through the Bragg cell effectively modulating/encrypting the chaotic output emanating from the device when operated within the chaotic regime. The encrypted signals are transmitted either via free-space or a waveguide, and thereafter received and demodulated using a heterodyne strategy. The resulting encryption and recovery at the receiver are examined especially from the perspective of overall accuracy and robustness of the system.

9216-26, Session 7

Residue number system based distributed arithmetic approach for optical-OFDM system

Kamaljit Singh Bhatia, Gurinder Singh, Tarandip Singh, Harpreet Singh, Sri Guru Granth Sahib World Univ. (India)

OFDM symbols obtained by overlapping of sub carriers orthogonally without causing inter carrier interference (ICI) and inter symbol interference (ISI) even for multichannel optical communication systems. Because of quite complex circuitry for multiuser optical-OFDM systems propagation time, effective Peak-to average power ratio (PAPR), frequency offset is a very big challenge. Keeping into view such challenges, in this paper we presents the modified RNS (Residue Number system) based DA (Distributed Arithmetic) approach to calculate the inner product computation in FIR filters. In the proposed approach(as shown in conceptual diagram) the input data is converted into residue number system domain by using parallel processing which provides high speed computation after that encoded into thermometer code format and the output is encoded into one-hot code format. The proposed thermometer code format provides a easy way to compute the modular inner products due to the absence of 2n modulo operation as compared to the conventional distributed arithmetic technique. As the critical path is associated with carry propagation, the absence of the carry propagation in residue number system provides high speed processing between the arithmetic blocks. The large words are encoded into small words which results in critical path minimization.

9216-27, Session 7

A novel evolution to remodulated WDM-PON based on DPSK/ASK orthogonal modulation

Qirui Zhou, Jun Ma, Zhejiang Univ. (China); Yang Lu, Hangzhou Dianzi Univ. (China); Lingchen Huang, Biao Chen, Zhejiang Univ. (China)

In recent years, as the demand for bandwidth grows rapidly, traditional time division multiplexing passive optical network (TDM-PON) faces serious challenges. The wavelength division multiplexing passive optical network (WDM-PON), by contrast, is considered as a promising next generation access network technology. However, the industry for WDM-PON is immature now, resulting in higher cost of WDN-PON compared with that of TDM-PON. So the evolution from TDM-PON to WDM-PON will be gradual, rather than immediate. For a time, TDM-PON and WDM-PON will work together before TDM-PON is discarded. In this paper, a smooth evolution scheme from legacy TDM-PON to the next generation WDM-PON with PolSK/ASK orthogonal modulation is proposed. The new WDM-PON is added into the existing PON infrastructure and coexists with the current TDM-PON. To eliminate any change requirement for the existing TDM-PON, PolSK is applied for WDM-PON downstream transmission. Meanwhile, upstream remodualtion is applied to achieve colorless ONUs in WDM-PON. For uplink remodulation, compared with ASK downlink signal, PolSK downlink signal induces much less crosstalk to the upstream signal, without requirement of erasing the downstream signal or low extinction ratio of downstream signal. The application of PolSK/ASK reduces both crosstalk from coexisting and remodulation. Error free operation is experimentally achieved for all downstream signals after 25 km SMF transmission. The power penalty of the ASK signal coexisting with PolSK signal is only 0.6dBm. The experiment results show the crosstalk is very little. Good performance is achieved for both unchanged coexisting TDM-PON and WDM-PON remodulated upstream signals in our proposed scheme.

9216-28, Session 7

Numerical investigation of the nonlinear dynamics of a hybrid acousto-optic Bragg cell with a variable feedback gain

Monish R. Chatterjee, Hao Zhou, Univ. of Dayton (United States)

Since around 1979, the operation of an acousto-optic Bragg cell under positive first-order feedback via amplification and delay in the loop has been studied extensively by several groups [1-3]. It is well-known that this system offers interesting dynamical properties, including bistability and chaos under a range of parameter thresholds. Thus, for fixed values of the bias voltage, feedback gain, feedback time delay (TD), incident optical intensity (Iinc) and initial first-order intensity (I1(0)), the hybrid system may be operated in regimes where it is bistable (thus leading to possible logical applications), or chaotic (within which it may exhibit period-2, period-3 and similar characteristics). In recent work, the analysis of the system was extended to include bistable maps and Lyapunov exponents specific to chaotic regimes whereby chaotic passbands and stopbands were established. Additionally, the system was utilized for signal encryption and decryption applications under chaos for uniform plane waves. The present work originated with the problem of a variable aperture opening relative to the first-order light. This potentially complex problem is simplified by assuming instead a variable feedback gain, which leads to considerably different nonlinear dynamics. This paper explores initially the simpler stages of this problem by examining the nonlinear dynamics versus the (DC) bias voltage for different variable-gain conditions, including very slow and likewise fast rates of change of the gain with time in relation to the feedback delay. It is found that the response depends critically on the rate of rise of the feedback gain, and also that the resulting chaotic regimes are generally significantly different from those for fixed values of the feedback gain.

9216-29, Session 8

Hybrid optoelectronic correlator (HOC) architecture for shift, scale, and rotation invariant target recognition incorporating polar mellin transform (PMT)

Mehjabin S. Monjur, Northwestern Univ. (United States); Shih Tseng, Northwestern Univ. (United States) and Digital Optics Technologies, Inc. (United States); Selim M. Shahriar, Northwestern Univ. (United States)

Optical target recognition using correlators is an important technique for fast verification and identification of images. The Hybrid Optoelectronic Correlator (HOC) overcomes the material problems of Vander Lugt and Joint Transform type correlators, using only photo-detectors, spatial light modulator (SLM) and field programmable gate arrays (FPGAs). In the HOC, the amplitude and phase information of the fourier transform of an object and that of a reference image are recorded with photo-detectors via interference with plane waves. The output of such an HOC has four terms: two convolution signals and two cross-correlation signals. By implementing a phase stabilization and scanning circuit, the convolution terms can be eliminated, so that an HOC becomes nearly identical to a conventional holographic correlator (CHC). To achieve the ultimate speed of such a correlator, we also propose an integrated graphic processing unit (IGPU), which performs all the electrical processes in a parallel manner. The HOC architecture along with the phase stabilization technique would be capable of high-speed image recognition in a translation-invariant manner. Furthermore, we show that the HOC architecture can be extended to scale and rotation invariant recognition by incorporating polar mellin transform (PMT). We also show how multiple objects can be recognized simultaneously in a scale and rotation invariant manner, a process previously thought to be incompatible with a PMT based correlator. We will present the architecture of this correlator, as well as results from the experimental efforts underway in our laboratory to demonstrate its capabilities using bulk components.

9216-30, Session 8

Holographic MINACE filters for 4f correlator

Nikolay N. Evtikhiev, Dmitry V. Shaulskiy, Rostislav S. Starikov, Sergey N. Starikov, Evgeny Y. Zlokazov, National Research Nuclear Univ. MEPhI (Russian Federation)

Results of MINACE filter implementation in 4f correlator are represented. We address the recognition problem of grayscale images of object subjected to out-of-plane rotation distortion. Our results of filter discriminating characteristic analysis are shown. We consider filter realization as computer generated hologram. The results of holographic filter implementation modeling in 4-f correlator are represented.

9216-31, Session 8

A distortion invariant method with optical computing for scene matching

Tianxiang Zheng, Yan Zhao, Liangcai Cao, Qingsheng He, Guofan Jin, Tsinghua Univ. (China)

Optical pattern recognition has been a vibrant area of research [1]. Systems based on a large number of correlation templates are powerful tools for many applications, including scene matching, verification, security, navigation, etc. A target image is captured in real time and usually contains the distortions with respect to the pre-stored template images in the volume holographic correlator. The scale and rotation variations of the target image are the main factors those affect the matching accuracy [2]. In the paper, a correlation-based method is proposed to eliminate the effects of the image scale and rotation variations onto the matching accuracy [3]. Based on the stationary random properties of the remote sensing images, a correlation model is proposed to resolve the effects of the image scale, rotation and translation on the correlation value in scene matching. The scale and the rotation of the target image are measured with the scale-scanning and rotation-scanning methods, respectively. The range and the accuracy of the rotation measurement are ±5° and 0.1°, respectively. The range and accuracy of the scale measurement are 0.8~1.2 and 0.003, respectively. The scale and rotation of the target image are compensated before performing the scene matching. After the compensation, the image recognition accuracy in scene matching reaches sub-pixel. The time consuming of the scene matching task will be estimated with an optical system. The method offers a good solution for scene matching in real time applications.

9216-32, Session 8

Pattern recognition of electromagnetic field scattering from anthropogenic objects on underlying surface

Denis A. Zherdev, Vladimir A. Fursov, Samara State Aerospace Univ. (Russian Federation)

The solution of electromagnetic scattering radiation problem is very important and has a wide application in practice, e.g. in navigation systems, in problem determining type the anthropogenic object. Often, as a sign of anthropogenic objects recognition using the radar object characteristic as radar cross section, as well as the radar cross section diagram. The process of determining these characteristics of objects is quite a difficult task. Typically for such purposes the object model with similar electromagnetic properties are placed in an anechoic chamber or in special testing area for test exposures registration.

Very accurate experimental study of the radar targets scattering properties and establishment statistically informative databases containing scattering diagram of different nature objects, is very costly and resource intensive. In this manner, the development of computer technology for efficient radiolocation characteristic modeling of

anthropogenic objects is a very important job. Therefore to determine the anthropogenic object type is sufficient to store only some basic model of object and terrain, which is used for obtain the reference scattering diagram of model with specific characteristics: the type of the underlying surface, the angle of observation, the characteristics of the atmosphere, etc.

In this paper is viewed the finite-difference time-domain simulation method for electromagnetic field scattering from various objects on the underlying surface. To find the field in the far-point is used near to far field conversion method. To find the values of the body scattered field is used such additional equipment as a method of total field separation on the incident and scattered fields.

9216-33, Session 9

Unitary implementation of the discrete two dimensional non-separable linear canonical transform

Liang Zhao, Univ. College Dublin (Ireland); John J. Healy, National Univ. of Ireland, Maynooth (Ireland); John T. Sheridan, Univ. College Dublin (Ireland)

The continuous linear canonical transforms is known to describes wave field propagation through paraxial (quadratic phase) optical systems. Digital algorithms to numerically calculate the LCT are therefore important in modelling field propagation through first order optical systems and are also of interest for many purely digital signal processing applications. Significantly the continuous LCTs are unitary, but discretisation can destroy this property resulting in a loss of conservative properties. Previously we presented a sufficient condition on the sampling rates chosen during discretisation to ensure that digital implementations of the 1D and 2D separable LCTs were unitary. In this paper we extend our analysis to discuss the cases of the 2D non-separable LCT which are used to describe complex anamorphic systems. We also examine the consequences of ours results.

9216-34, Session 9

Wavelet-domain de-noising technique for THz pulsed spectroscopy

Nikita V. Chernomyrdin, Kirill I. Zaytsev, Irina N. Fokina, Valeriy E. Karasik, Arsenii A. Gavdush, Bauman Moscow State Technical Univ. (Russian Federation)

De-noising of terahertz time-domain spectroscopy (TDS) data is an essential problem, since a noise in the TDS system data prevents correct reconstruction of the sample spectral dielectric properties and to perform the sample internal structure studying. There are certain regions in TDS signal Fourier spectrum, where Fourier-domain signal-to-noise ratio is relatively small. Effective de-noising might potentially expand the range of spectrometer spectral sensitivity. In this work it is shown how the recent progress in signal processing in wavelet-domain could be used for TDS de-noising. It demonstrates the ability to perform effective de-noising of TDS data using the algorithm of the Fast Wavelet Transform (FWT). The results of the optimal wavelet basis selection and wavelet-domain thresholding technique selection are reported. Wavelet-domain de-noising algorithm was successfully implemented in TDS signal processing. These results are discussed in this paper, and also a technique for automatic construction of the wavelet-domain de-noising procedure is offered. The stability of de-noising procedure in presence of white Gaussian noise was studying by means of numerical simulation.

9216-35, Session 9

Statistical study of coherent images of particles in the volume of optical medium

Tatiana Y. Nikolaeva, Nikolay V. Petrov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

This paper is devoted to the problems of recognition of individual particle images in the volume of the optical medium conditioned upon their coherent superposition. Methods of statistical analysis of parameters of particles are reviewed - particle image velocimetry methods in comparison with methods of speckle correlation. To evaluate the efficiency of methods of particle image recognition, a typical problem of analysis of formed by an optical system intensity distributions of laser radiation scattered on suspended particles in a volume of optical medium is considered. To accomplish this, we have developed a specialized software package that solves the following tasks: 1) modeling of the volume of optical medium with different statistical distributions of particles; 2) optical imaging of particles by an optical system using numerical simulation based on the scalar diffraction theory (angular spectrum method, method of convolution of the source field with the system's impulse response); 3) recognition and statistical processing of the image of particles in a volume of the optical medium formed by the optical system. Therefore, software model was created as a convenient tool for the study of the formation process of speckle patterns with increase of concentration of particles in the volume and analysis of performance efficiency of recognition methods of individual particle images, which is estimated as the ratio between the number of recognized particles in the volume defined by depth of field and initial concentration of particles.

9216-36, Session 9

A fast and automatic fusion algorithm for unregistered multiexposure image sequence

Yan Liu, Feihong Yu, Zhejiang Univ. (China)

Human visual system (HVS) can visualize all the brightness levels of the scene through visual adaptation. However, the dynamic range of most commercial digital cameras and display devices are smaller than the dynamic range of human eye. This implies low dynamic range (LDR) images captured by normal digital camera may lose image details. We propose an efficient approach to high dynamic (HDR) image fusion that copes with image displacement and image blur degradation in a computationally efficient manner, which is suitable for implementation on mobile devices. The various image registration algorithms proposed in the previous literatures are unable to meet the efficiency and performance requirements in the application of mobile devices. To improve the accuracy of the algorithm proposed in this paper, we introduce entropy theory to the selection of the reference image. In this paper, we selected Speeded up Robust Features (SURF) detector to extract local image structures, which is more robust to image blur. The descriptor selected in multiexposure image fusion algorithm for mobile device has to be fast and robust to illumination variations and geometric deformations. Fast Retina Keypoint (FREAK) descriptor is the best candidate in our algorithm. Further, we perform an improved RANdom Sample Consensus (RANSAC) algorithm to reject incorrect matches. For the fusion of images, a new approach based on Stationary Wavelet Transform (SWT) is used. The experimental results demonstrate that the proposed algorithm generates high quality images at low computational cost. Comparisons with a number of other feature matching methods show that our method gets better performance.

9216-37, Session 9

An ARMA model based motion artifact reduction algorithm in fNIRS data through a Kalman filtering approach

Mehdi Amian, S. Kamaledin Setarehdan, Univ. of Tehran (Iran, Islamic Republic of); Hamed Yousefi, School of Electrical and Computer Eng., College of Engineering, University of Tehran (Iran, Islamic Republic of)

Functional Near infrared spectroscopy (fNIRS) is a newly noninvasive way to measure oxy hemoglobin and deoxy hemoglobin concentration changes of human brain. Relatively safe and affordable than other functional imaging techniques such as fMRI, it is widely used for some special applications such as infant examinations and pilot's brain monitoring. In such applications, fNIRS data sometimes suffer from undesirable movements of subject's head which called motion artifact and lead to a signal corruption. Motion artifact in fNIRS data may result in fallacy of concluding or diagnosis. In this work we try to reduce these artifacts by a novel Kalman filtering algorithm that is based on an autoregressive moving average (ARMA) model for fNIRS system. Our proposed method does not require to any additional hardware and sensor and also it does not need to whole data together that once were of ineluctable necessity in older algorithms such as adaptive filter and Wiener filtering. Results show that our approach is successful in cleaning contaminated fNIRS data.

9217-1, Session 1

High accuracy image restoration method for seeing through water

Kalyan K. Halder, UNSW Canberra (Australia); Murat Tahtali, Sreenatha G. Anavatti, UNSW@ADFA (Australia)

The restoration of a sequence of underwater images distorted by water waves is a challenging task. This paper presents a new approach for geometrical corrections of the turbulence degraded frames of an underwater object or scene. This approach is based on computing the centroid image of the sequence through an iterative scheme. A robust image registration technique is employed for pixel registration of all the frames against a reference frame and determines the pixel shift maps. Using these shift maps, each distorted frame is dewarped. A non-local means filter is used to mitigate the noise and improve the signal-to-noise ratio (SNR) of the dewarped frames. A performance comparison between our proposed restoration approach and the state-of-the-art technique is presented in terms of restoration time and accuracy. The effectiveness of our approach is demonstrated on both synthetic and real-world underwater videos.

9217-2, Session 1

Reconstruction algorithms for compressive hyperspectral imaging systems with separable spatial and spectral operators

Yaniv Oiknine, Yitzhak August, Adrian Stern, Ben-Gurion Univ. of the Negev (Israel)

Recently we introduced a hyperspectral compressive sensing scheme that uses separable projections in the spatial and spectral domains. The separable encoding schemes facilities the optical implementation, reduces dramatically the computational burden, and storage requirements. Owing to this benefits we were been able to encode the hyperspectral cube in its all three dimensions. We note that previous methods for compressive hyperspectral sensing were limited to random encoding only in two dimensions. In this work we present a comparison between various reconstruction methods applied for the for hyperspctral data captured with our separable compressive sensing systems. We compare several algorithms and several wavelet transforms used as sparsifiers.

9217-3, Session 1

Distortion operator kernel and accuracy of iterative image restoration

Artyom Makovetskii, Chelyabinsk State Univ. (Russian Federation); Vitaly Kober, Ctr. de Investigación Científica y de Educación Superior de Ensenada B.C. (Mexico)

Variational functionals are commonly used restoration of images distorted by a linear operator. Numerous restoration techniques optimized with respect to different metrics were introduced to solve the problem. A common way to find the minimum of a functional is to utilize the gradient descent method. In this paper, we analyze the gradient descent method in the frequency domain and show the method converges to the sum of an original undistorted function and the kernel of a linear distortion operator. For uniform linear degradation the kernel function is oscillating. So, the restoration accuracy of linearly degraded image depends on the kernel function. The accuracy can be improved by consequent smoothing with the total variation method. It was shown that the use of metrical as well as topological characteristics can improve the restoration quality. The topological characteristics of a function of two variables are linear variations. The proposed topological method of consequent image smoothing modifies the result of the total variation-based method in order to obtain a given number of linear variations at the output. Computer simulation results are provided to illustrate the performance of the proposed algorithm for restoration of linearly degraded images in terms of restoration accuracy.

9217-4, Session 1

Nonlinear filtering for character recognition in low quality document images

Julia Diaz, Vitaly Kober, Ctr. de Investigación Científica y de Educación Superior de Ensenada B.C. (Mexico)

Optical character recognition (OCR) in scanned printed documents is a well-studied task, where the captured conditions like sheet position, illumination, contrast and resolution are controlled. Many OCR algorithms proposed and utilized in numerous systems such as ABBYY possess a good recognition performance. However, nowadays it is more practical to use mobile devices for document capture than a scanner. So, as a consequence, the quality of document images often is poor owing to presence of geometric distortions, nonhomogeneous illumination, low resolution, etc. It affects to the performance of common OCR engines. In this work we propose to use multiple adaptive nonlinear composite filters for detection and classification of characters. The suggested approach is based on threshold decomposition and illumination-invariant morphological correlation. The composite filters are designed by incorporating information from a set of training images. In the iterative training stage they achieve a given value of discrimination capability. Finally, computer simulation results obtained with the proposed system are presented and compared with those of common algorithms and systems in terms of misclassification errors.

9217-5, Session 1

Color image restoration based on camera microscanning

Jose L. Lopez-Martinez, Univ. Autónoma de Yucatán (Mexico); Vitaly Kober, Ctr. de Investigación Científica y de Educación Superior de Ensenada B.C. (Mexico); Manuel Escalante-Torres, Univ. Autónoma de Yucatán (Mexico)

Recently, a blind image restoration algorithm based on camera microscanning was proposed. The method deals with additive, multiplicative, impulsive interferences, and sensor's noise. The method restores a single image from degraded images captured with an array imaging system that is subject to mechanical isotropic displacement. However, the method recovers a monochromatic image from observed gray level images. In this work, we propose a method to restore color images from a set degraded color images obtained with a microscanning imaging system. Using a set of observed images, image restoration is carried out by solving a system of equations that is derived from optimization of an objective function. Since the proposed method possesses a high computational complexity, a fast algorithm is developed. Experimental and computer simulation results obtained with the proposed method are analyzed in terms of restoration accuracy, tolerance to additive input noise, and robustness to sensor's misregistration.

9217-6, Session 1

Scene-based nonuniformity correction with an anisotropic LMS algorithm for infrared images

Lixiang Geng, Qian Chen, Weixian Qian, Guohua Gu, Nanjing Univ. of Science and Technology (China); Mengdi Yuan, Nanjing Univ. of Technology (China)

Nowadays, infrared imaging (IR) devices are mostly based on a focal-plane array (FPA) structure which suffer from the fixed pattern noise (FPN) due to nonuniform response of the FPA structure. The scene-based nonuniformity correction (SBNUC) algorithms based on Least mean squares (LMS) is very popular currently. In this paper, a novel SBNUC method is proposed which is designed with a LMS of faster convergence. Unlike the conventional LMS NUC methods which use the adjacent information to design the “desired” image with the isotropic image filter, the proposed method will produce the “desired” image with an anisotropic image filter. The coefficients of the anisotropic filter is designed to be different respect to the orientation. Since the coefficients of the isotropic filter in the conventional algorithms are equal for different orientations, the problems of low convergence speed and ghosting artifacts will be brought out. However, the anisotropic filter make the “desired” image more desired that is more similar to the true image so that less error between the “desired” and true image and less ghosting artifacts remain in the results. As the “desired” image is more ideal, the update pace of LMS filter can be designed more large which will lead to a more fast convergence speed. The coefficients of the anisotropic filter and the update pace of the LMS should be deliberated integrally. Finally, the performance of the proposed algorithm is evaluated with infrared image sequences with simulated and real fixed-pattern noise. Compared with other nonuniformity correction techniques, the results of experiments for the proposed method significantly show a more reliable ability to compensate for nonuniformity and achieve a fast convergence.

9217-7, Session 1

Study of adaptive correlation filter synthesis guided by the peak and shape of the correlation output

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In recent year’s many proposals that considers a adaptive perspective have been developed to solve some drawbacks like geometric distortions, background noise and target discrimination but metrics used for that, only are based in the output correlation peak. In this paper is studied the correlation shape to implement adaptive correlation filters guide by the peak and shape of the correlation output. Also shape is used to guide the search for the bank filters. The guide used for synthesis is a fusion synthesis from both features; this implies the possibility to used parallel tools. Respect to the search in the filters bank, the shape of correlation output is used as study of correlation output to correlate just a few filters instead that all filters bank. Results about times of synthesis, performance of filters, comparatives with adaptive proposals are obtained.

9217-8, Session 1

Digital deblurring based on linear-scale differential analysis

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Existing methods of deblurring, such as unsharp masking or local contrast enhancement, often lead to artifacts and halos along the object boundaries. More sophisticated algorithms, such as deconvolution with known distorting kernels, or blind deconvolution, require significant computing resources and can not be used for implementation in real-time. We propose a simple artifact-free method for enchancing the sharpness of digital images. The method is based on the computation of a number of two-dimensional data sets corresponding to the differential responses in several linearly varying scales, followed by transposition and summing up the data with weights, derived from the original distorted image. We found that the number of differential scales needed for efficiend deblur is proportional to the strendth of the blur. The application of the method does not require any preliminary definition of the parameters, and it can be applied to improve images with arbitrary distorting kernels. The method is tested on the blood cell images obtained from a digital microscope. The processing speed is much higher than that achievable with direct deconvolution, making the method a good candidate for applications in direct video processing.

9217-56, Session 1

Full-body gestures and movements recognition: user descriptive and unsupervised learning approaches in GDL classifier

Tomasz Hachaj, Cracow Pedagogical Univ. (Poland); Marek R. Ogiela, AGH Univ. of Science and Technology (Poland)

Gesture Description Language (GDL) is a classifier that enables syntactic description and real time recognition of full-body gestures and movements. Gestures are described in dedicated computer language named Gesture Description Language script (GDLs). GDL is formal context-free grammar. The basic assumption under GDL and GDLs was to create the pattern recognition procedure and description intuitive and in the same time keeping high effectiveness of methodology. The GDL technology is well established and has already proved to be reliable tool for full-body gestures and movements recognition both in commercial and scientific applications. However, due to limitations of GDLs, it was difficult to precisely analyze trajectories of movements. Also GDLs descriptions had to be made manually. In this paper we will present methods to overcome both of those problems.

At first we will introduce new GDLs formalisms that enable recognition of selected classes of movement trajectories (for example collinearity of movement samples).

The second novelty is new unsupervised learning method with which it is possible to automatically generate GDLs descriptions. The proposed algorithm uses gestures recordings to construct set of GDLs rules that can be used to classify movements. We will call this approach Reversed-GDL (R-GDL). What is more, the syntactic descriptions that are generated by R-GDL can be very easily interpreted by the user giving valuable information about observed movements.

We have initially evaluated both proposed extensions of GDL and we have obtained very promising results. Both the novel methodology and evaluation results will be described in this paper.

9217-9, Session 2

prediction-guided quantization for video tone mapping

Agnes Le Dauphin, Ronan Boitard, Dominique Thoreau, Yannick Olivier, Edouard Francois, Fabrice LeLéannec, Technicolor S.A. (France)

Tone Mapping Operators (TMOs) compress High Dynamic Range (HDR) contents to address Low Dynamic Range (LDR) displays. However, before reaching the end-user, these contents are usually compressed using a codec (coder-decoder) for broadcasting or storage purposes.

Achieving the best trade-off between rendering and compression efficiency is of prime importance. Any TMO includes a rounding quantization to convert floating point values to integer ones. In this work, we propose to adapt this rounding, in the coding loop, to increase the compression efficiency of the tone mapped video content. Our technique provides an appropriated quantization for each mode of both the intra and inter prediction. The mode that minimizes a rate-distortion criterion uses its corresponding quantization to provide integer values for the rest of the encoding process. Preliminary results with HEVC (HM12.0) provides a reduction of up to 12% of the total bit-rate as well as an average bit-rate reduction of 8.5% for all the test sequences.

9217-10, Session 2

Performance evaluation of objective quality metrics for HDR image compression

Giuseppe Valenzise, Francesca De Simone, Télécom ParisTech (France); Paul Lauga, Institut Mines-Telecom, Telecom ParisTech, CNRS LTCI (France); Frederic Dufaux, Télécom ParisTech (France)

The quality of experience of High Dynamic Range (HDR) content is influenced by many factors, such as the way pictures are generated and displayed. For the same acquisition and rendering conditions, HDR pictures of diverse scenes may actually entail a radically different visual experience, depending on the content of the scene. In order to select video content for the evaluation of HDR processing techniques, it is therefore necessary to develop computational methods able to measure the HDR characteristics of a scene, similarly to what the Spatial Information (SI) or Temporal Information (TI) do for LDR spatial and temporal complexity, respectively. In this paper we propose a dynamic range index (DRI) which quantifies the characteristics related to the dynamic range of HDR video sequences. Specifically, we formalize the DRI as the loss of contrast between HDR images and their projection on a LDR subspace represented by conventional 8 bits per pixel image, and we evaluate our analysis through subjective tests performed on a HDR display.

9217-11, Session 2

Crowdsourcing evaluation of high dynamic range image compression

Philippe Hanhart, Pavel Korshunov, Touradj Ebrahimi, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

No Abstract Available

9217-12, Session 2

Evaluation of privacy in high dynamic range video sequences

Martin Rerabek, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Lukáš Krasula, Karel Fliegel, Czech Technical Univ. in Prague (Czech Republic); Touradj Ebrahimi, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

No Abstract Available

9217-13, Session 2

I-Vectors for image classification

David C. Smith, National Security Agency (United States)

Recent state-of-the-art work on speaker recognition and verification uses a simple factor analysis to derive a low-dimensional “total variability space” which simultaneously captures speaker and channel variability. This approach simplified earlier work using joint factor analysis to separately model speaker and channel variability. Here we adapt this “i-vector” method to image classification by replacing speakers with image categories, voice cuts with images, and cepstral features with SURF local descriptors, and where the role of channel variability is attributed to differences in image backgrounds or lighting conditions. A Universal Gaussian mixture model (UGMM) is trained (unsupervised) on SURF descriptors extracted from a varied and extensive image corpus. Individual images are modeled by additively perturbing the supervector of stacked means of this UGMM by the product of a low-rank total variability matrix (TVM) and a normally distributed hidden random vector, Y. The TVM is learned by applying an EM algorithm to maximize the sum of log-likelihoods of descriptors extracted from training images, where the likelihoods are computed with respect to the GMM obtained by perturbing the UGMM means via the TVM as above, and leaving UGMM covariances unchanged. Finally, the low-dimensional i-vector representation of an image is the expected value of the posterior distribution of Y conditioned on the image’s descriptors, and is computed via straighforward matrix manipulations involving the TVM and image-specific Baum-Welch statistics. We compare classification rates found with (i) i-vectors, (ii) PCA, (iii) Discriminant Attribute Projection (the last two trained on MAP-adapted Gaussian supervector image representations), and (iv) by replacing the TVM with the the matrix of dominant PCA eigenvectors before i-vector extraction.

9217-14, Session 2

Classification and quantification of suspended dust from steel plants by using color and transmission image analysis

Yoshiyuki Umegaki, Akira Kazama, JFE Steel Corp. (Japan); Yoshinori Fukuda, JFE Techno-Research Corp. (Japan)

Suspended dust is constantly monitored in and around JFE Steel’s steel plants to prevent scattering to the surrounding area. Dust from steel plants includes particles of three color types, black particles (coke, coal), red particles (iron ore, sintered ore) and white particles (slag, lime). It also includes silica sand which does not derive from steelmaking. For monitoring, dust is trapped by exposing adhesive tape in the atmosphere at observation points, and the particles of each color type are visually counted by using a microscope. However, the accuracy of the results depended on the operator, and the operation was also troublesome. To achieve efficient, operator-independent measurement, a system that can classify and quantify dust particles automatically was developed. The system extracts particles from color images of dust on the tape lighted from above and classifies the particles into three color types. These processes are done basically in YCrCb color space, where colors are represented by luminance (Y) and chrominance (Cr and Cb). YCrCb color space is more manageable than RGB color space for visual operation. To exclude silica sand from the extracted particles, transmission images obtained by backlighting the dust are also used. In these images, silica sand appears semi-transparent and therefore can be distinguished from steelmaking-related dust. The system finally outputs the amount and area of the classified particles by color type, approach direction and diameter. The system assists operators and has also contributed to identifying dust sources and scattering routes in JFE’s plants.

9217-15, Session 2

Recognition of similar objects by linear correlation filters

Jose R. Jaquez, Vitaly Kober, Ctr. de Investigación Científica y de Educación Superior de Ensenada B.C. (Mexico)

Many different methods of pattern recognition have been proposed in the last years. Nowadays there are several techniques for object recognition whose performance is limited owing to either distortions of observed scenes or similarity of different objects. Reliable recognition and classification of similar objects is still open problem. To solve the problem several approaches were used such as feature-based matching, adaptive filtering, and frequency blocking techniques. Since the difference between features of similar objects (histogram of oriented gradients, scale-invariant key points, and etc.) is often negligible, the rate of matching errors is high. It is known, that a frequency blocking technique helps in the design of a linear filter for reliable discrimination of two similar objects. Adaptive approach is used to achieve a desired level of discrimination between several similar objects. A bank of adaptive filters can be used for the design a system for multiclass recognition and classification of numerous similar objects at high rate. In this work, we propose to design a system based on blocking technique and adaptive filtering for reliable recognition and classification of similar objects. To improve the performance of the system and to reduce its computational complexity genetic algorithms are utilized. Computer simulation results are provided and discussed.

9217-16, Session 2

System for objective assessment of image differences in digital cinema

Karel Fliegel, Czech Technical Univ. in Prague (Czech Republic); Lukas Krasula, Czech Technical University in Prague (Czech Republic) and LUNAM University - IRCCyN CNRS UMR 6597 (France); Petr Pata, Czech Technical Univ. in Prague (Czech Republic); Jiri Myslik, Josef Pecak, Marek Jicha, Film and TV School of Academy of Performing Arts in Prague (Czech Republic)

There is high demand for quick digitization and subsequent image restoration of archived film records. Digitization is very urgent in many cases because various invaluable pieces of cultural heritage are stored on aging media. Only selected records can be reconstructed perfectly using painstaking manual or semi-automatic procedures. This paper aims to answer the question what are the quality requirements on the restoration process in order to obtain acceptably close visual perception of the digitally restored film in comparison to the original analog film copy. This knowledge is very important to preserve the original artistic intention of the movie producers. Subjective experiment with artificially distorted images has been conducted in order to answer the question what is the visual impact of common image distortions in digital cinema. Typical color and contrast distortions were introduced and test images were presented to viewers using digital projector. Based on the outcome of this subjective evaluation a system for objective assessment of image distortions has been developed and its performance tested. The system utilizes calibrated digital single-lens reflex camera and subsequent analysis of suitable features of images captured from the projection screen. The evaluation of captured image data has been optimized in order to obtain predicted differences between the reference and distorted images while achieving high correlation with the results of subjective assessment. The system can be used to objectively determine the difference between analog film and digital cinema images on the projection screen.

9217-17, Session 2

Open source database of images DEIMOS: extension for large-scale subjective image quality assessment

Stanislav Vítek, Czech Technical Univ. in Prague (Czech Republic)

DEIMOS (Database of Images: Open Source) is an open-source database of images and video sequences for testing, verification and comparison of various image and/or video processing techniques such as compression, reconstruction and enhancement. This paper deals with extension of the database allowing performing large-scale web-based subjective image quality assessment. Extension implements both administrative and client interface. The proposed system is aimed mainly at mobile communication devices, taking into account advantages of HTML5 technology; it means that participants don't need to install any application and assessment could be performed using web browser. The assessment campaign administrator can select images from the large database and then apply rules defined by various test procedure recommendations. The standard test procedures may be fully customized and saved as a template. Alternatively the administrator can define a custom test, using images from the pool and other components, such as evaluating forms and ongoing questionnaires. Image sequence is delivered to the online client, e.g. smartphone or tablet, as a fully automated assessment sequence or viewer can decide on timing of the assessment if required. Environmental data and viewing conditions (e.g. illumination, screen brightness, screen resolution, noise levels, vibrations, GPS coordinates, eye movements), may be collected and subsequently analyzed.

9217-18, Session 2

MTF analysis for coded aperture imaging in a flat panel display

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In this paper, we analyze the modulation transfer function (MTF) of coded aperture imaging in a flat panel display. The flat panel display with a sensor panel forms lens-less multi-view cameras through the imaging pattern of the modified redundant arrays (MURA) on the display panel. To analyze the MTF of the coded aperture imaging implemented on the display panel, we first mathematically model the encoding process of coded aperture imaging, where the projected image on the sensor panel is modeled as a convolution of the scaled object and a function of the imaging pattern. Then, system point spread function is determined by incorporating a decoding process which is dependent on the pixel pitch of the display screen and the decoding function. Finally, the MTF of the system is derived by the magnitude of the Fourier transform of the determined system point spread function. To demonstrate the validity of the mathematically derived MTF in the system, we build a coded aperture imaging system that can capture the scene in front of the display, where the system consists of a display screen and a sensor panel. Experimental results show that the derived MTF of coded aperture imaging in a flat panel display system well corresponds to the measured MTF.

9217-86, Session 2

Subjective evaluation of higher dynamic range video

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No Abstract Available

9217-55, Session PMon

Heterogeneous iris image hallucination using sparse representation on a learned heterogeneous patch dictionary

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Cross sensor iris matching may seriously degrade the recognition performance because of the sensor mismatch problem between iris image enrollment and test stage. In this paper, we propose two novel patch-based heterogeneous dictionary learning method to attack this problem. The first method applies the latest sparse representation theory while the second method tries to learn the correspondence relationship through PCA in heterogeneous patch space. Both methods learn the basic atoms in iris textures across different image sensors and build connections between them. After such connections are built, at test stage, it is possible to hallucinate (synthesize) iris images across different sensors. By matching training images with hallucinated images, the recognition rate can be successfully enhanced. The experimental results showed the satisfied results both visually and in terms of recognition rate. Experimenting with an iris database consisting of 3015 images, we show that the EER is decreased 82.03% relatively by the proposed method.

9217-67, Session PMon

Biometric analysis of the palm vein distribution by means two differet techniques of feature extraction

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Veins pattern can be used for accessing, identifying, authenticating purposes, which is more reliable than traditional identification way. As the blood vessels are hidden underneath the skin and are mostly invisible to the human eye, vein patterns are much harder for intruders to copy compared to other biometric traits. Furthermore, this pattern can be used for venipuncture in the health field to locate veins of patients when they cannot be seen with the naked eye.

In this study, an image acquisition system was implemented in order to acquire digital images of the hands of people in the near infrared. The image acquisition system consists of a CCD camera and a light source with emission in the near infrared. This radiation can penetrate and be absorbed greatly by the desoxyhemoglobin present in the blood of the veins. The enhancement of acquired images is given by a low-pass filter and adaptive thresholding in order to obtain the distribution of vein patterns.

The above process is focused on people recognition through of images of palm-dorsal distribution obtained in the near infrared making a comparison of different techniques of feature extraction as moments, veincode, reference point, correlation and Radon transform. The classification task is achieved using Artificial Neural Networks. Two databases were used for the analysis of the performance of the algorithms. The first one is PolyU Multispectral Palmprint Database and the second in our home database.

The results show that moments have a 91%, veincode has an 85%, reference point has 79%, correlation has 90% and Radon transform has 89% of correct rate classification.

9217-68, Session PMon

Camera self-calibration's application in light pen visual measurement system

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A method for camera self-calibration based on planar template is introduced to the Monocular and Binocular Light Pen Visual Measurement System, which is developed by ourselves, and realized the calibration of cameras and the mark points on the pen. The cameras' internal parameters acquired by this method serve as initial values of the adjustment method, and an ideal result can be got by the iteration. In the system, the relative positions of the mark points on the pen and the center of the light pen's probe ball are uncertain, and the mark points are on a same plane approximately, so the self-calibration method can also be used to the reconstruction of these mark points and the calibration of the probe ball's center. Experiments show that in the 100mmx120mm field of view, the errors of the 42 points' positions measured by the monocular light pen system are less than 30um, and that are less than 15um in binocular occasions. In this calibration method, there is no restriction on camera's motion, the planar target is easier to make. Its application reduce the complexity of the system's measuring process, improve the efficiency and the measuring result is satisfying.

9217-69, Session PMon

A SVM training samples reduction strategy

Weimin Li, Yu-Wei Wang, Univ. of Science and Technology of China (China); Lichun Zhu, National Astronomical Observatories (China); Yu Zhao, Univ. of Science and Technology of China (China)

As a famous machine learning method, support vector machine (SVM) has wide applications in the field of pattern recognition. But under the large-scale sample set, the training efficiency is not satisfactory, in order to solve this problem,a training samples reduction strategy is proposed. .The method constructs a hyper plane over the origin in the kernel space,and the class-center vector as its normal vector, then selects boundary samples that may be support vectors as the training sample based on the size distribution of the distance between sample and hyper plane, so as to reduce the training samples.Experiments based on a standard UCI datasets show that this method can keep the testing accuracy and greatly improve the training speed.

9217-70, Session PMon

Early decision of TU split in HEVC using DC energy proportions

Jonghyun Ma, Yongjo Ahn, Donggyu Sim, Kwangwoon Univ. (Korea, Republic of)

This paper proposes an early decision of transform unit (TU) split for fast encoding in High Efficiency Video Coding (HEVC) based on the statistical analysis of transform coefficients. The computational complexity of TU split decision is high in the HEVC encoder. Therefore, there are several conventional algorithms for early TU decision; however, most of these algorithms exploit the distribution of transform coefficients which requires the transformation of residual data during the TU split decision. To reduce the computational complexity, the proposed algorithm performs the TU split decision without transformations. In the proposed algorithm, the TU split decision is performed by considering 'DC energy proportions,' which is the proportions of DC coefficient energy of split TUs and non-split TUs. Based on Parseval's theorem, the energy of TUs can be calculated in the spatial domain; therefore, the proposed algorithm computes the DC energy proportions without transformations for AC coefficients. Statistical analysis of TU split on the HM 12.0 reference software

encoder shows that TUs that are split by the rate-distortion optimization (RDO) process more likely have DC energy proportions on the particular range. Therefore, the probability of TU split with respect to DC energy proportions is modeled by a joint probabilistic model; in the proposed algorithm, a TU is split when the probability of the model is higher than a pre-calculated constant. Experimental results on HM 12.0 shows that the proposed algorithm reduces 10% of encoding time in average while the average BD-rate loss is below 0.5% under HEVC common test conditions.

9217-71, Session PMon

Principles of image processing in machine vision systems for the color analysis of minerals

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At the moment color sorting method is one of promising methods of mineral raw materials enrichment. This method is based on registration of color differences between images of analyzed objects.

As is generally known the problem with delimitation of close color tints when sorting low-contrast minerals is one of the main disadvantages of color sorting method. It is can be related with wrong choice of a color model and incomplete image processing in machine vision system for realizing color sorting algorithm.

Another problem is a necessity of image processing features reconfiguration when changing the type of analyzed minerals. This is due to the fact that optical properties of mineral samples vary from one mineral deposit to another. Therefore searching for values of image processing features is non-trivial task. And this task doesn't always have an acceptable solution.

In addition there are no uniform guidelines for determining criteria of mineral samples separation.

It is assumed that the process of image processing features reconfiguration had to be made by machine learning. But in practice it's carried out by adjusting the operating parameters which are satisfactory for one specific enrichment task. This approach usually leads to the fact that machine vision system unable to estimate rapidly the concentration rate of analyzed mineral ore by using color sorting method.

This paper presents the results of research aimed at addressing mentioned shortcomings in image processing organization for machine vision systems which are used to color sorting of mineral samples. The principles of color analysis for low-contrast minerals by using machine vision systems are also studied. In addition, a special processing algorithm for color images of mineral samples is developed. Mentioned algorithm allows you to determine automatically the criteria of mineral samples separation based on an analysis of representative mineral samples.

Experimental studies of the proposed algorithm were performed using samples of gold and copper-nickel ores. And obtained results confirmed its efficiency with respect to mineral objects.

The research results will allow:

– expanding the use of the color sorting method in the field of mineral raw materials enrichment;

– facilitating the search for values of image processing features for machine vision systems which are used to the color analysis of minerals;

– reducing the time required for reconfiguration of image processing features when changing the type of analyzed minerals;

– realizing the process of rapid estimating the concentration rate of analyzed mineral ore by using color sorting method.

9217-72, Session PMon

The empirical mode decomposition algorithm via fast fourier transform

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In this paper we solve a problem of Empirical Mode Decomposition (EMD) fast algorithm realization. EMD is one of the newest methods for decomposition of non-linear and non-stationary signals. A basis of EMD is formed “on-the-fly”, i.e. it depends from a distribution of the signal and not given a priori in contrast on cases of Fourier Transform (FT) or Wavelet Transform (WT).

The EMD requires interpolating of local extremes sets of signal to find upper and lower envelopes. The data interpolation on an irregular lattice is a very low-performance procedure. A classical description of EMD by Huang suggests doing this through splines, i.e. through a system of equations solving.

A fast algorithm existence is the main advantage of the FT. A simple description of an algorithm in terms of Fast Fourier Transform (FFT) is a standard practice to reduce operation's count. We propose a fast implementation of EMD (FEMD) through FFT and some other cost-efficient algorithms.

Basic two-stage interpolation algorithms for EMD are Upscale procedure through FFT and Downscale procedure through a signal's points selection. First we examine the local maxima (or minima) set without reference to the axis OX, i.e. on a regular lattice. The Upscale through the FFT change the signal's length to the Least Common Multiple (LCM) value of all distances between neighboring extremes on the axis OX. If the LCM value is too large the limitation of local extremes set must be performed. In this case it is an analog of the spline interpolation.

A demo for FEMD in noise reduction task for OCT and other spectroscopic application has been shown.

9217-73, Session PMon

Segmentation of astronomical images

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Object detection is one of the most important procedures in astronomical imaging.

This paper deals with segmentation of astronomical images based on pixelwise linear classifier (perceptron algorithm) and SVM (support vector machine). We consider astronomical image data acquired using a photometric system with B, V, R, I and N filters. Each image is acquired in more realizations. All image realizations are averaged to suppress unwanted noise. Then a profile photometry is applied to find possible position of stars. The pixelwise classifier is trained by B, V, R, I and N image vectors. Training samples are defined by user using rectangular regions (20 selections for both classes: object, background). A number of objects and their positions are compared with astronomical object catalogue. We can conclude that the performance of the presented technique is fully comparable to other SoA algorithms.

9217-74, Session PMon

Real time soft-partition-based weighted sum filtering with GPU acceleration

Shuqun Zhang, Bryan Furia, College of Staten Island (United States)

Recently image processing such as restoration, super-resolution and noise reduction using soft-partition based weighted sum filters have shown state-of-the-art results. Partition-based weighted sum filters are spatially adaptive filtering techniques by combining vector quantization and linear finite impulse response filtering concepts, which have shown to achieve much better results than spatial-invariant filtering methods. However, they are computationally prohibitive for practical applications because of enormous computation involved in both filtering and training. Real-time processing is impossible even for small window size. In this paper present a fast implementation of soft-partition based weighted sum filters by exploiting the massively parallel processing capabilities of a GPU within a CUDA framework owing to its easy off-the-shelf availability and programmer friendliness. To our knowledge there is no GPU implementation reported for partition based weighted sum filters yet. For the implementation, we focus on memory management, system design, and implementation strategies. The performance on various window sizes is measured and compared between GPU-based and CPU-based implementations. The results indicate that GPU-based implementation can significantly accelerate computations for filtering and training, and make real-time filtering become possible. Application in image restoration is also demonstrated.

9217-75, Session PMon

An object boundary detection system based on a 3D stereo monitor

Shuqun Zhang, Bryan Furia, College of Staten Island (United States)

Finding object boundary is one of the most challenging tasks in image processing, and it has important applications in many areas such as medical and biological imaging. Numerous image segmentation algorithms have been proposed to detect object boundary, among which active contours, level set methods and graph cut are widely used especially for medical images because of their good performance in segmentation. These algorithms are usually computational expensive due to many iterations needed and thus not suitable for real-time processing. Optical processing can be used for real-time object detection through utilizing parallel processing and implementing high-pass filters, but it is impractical due to coherent illumination needed and unsatisfied results. In this paper we propose a novel object boundary detection system based on a 3D stereo monitor. The image processing is based on controlling the polarization of LCD and the way the image is display on a 3D monitor to enhance object boundary. The users can see the enhanced contour of the object through a 3D polarization glasses in real-time, which can be also recorded using a camera for further processing. A software is developed for user interaction to achieve better results. The effectiveness of the system is demonstrated using various medical and biological images. It has the advantages of high speed processing and robustness to noise over the traditional methods.

9217-76, Session PMon

A super-resolution algorithm based on adaptive weighted total variation

Xun-Jie Zhao, Chengjin Li, Soochow Univ. (China); Xuesong Zhang, Science and Technology on Electro-optical Security Lab. (China)

In most electronic imaging applications, images with high resolution(HR) are desired and often required. However, theoretical and practical limitations usually constrain the achievable resolution of any imaging device. Image super-resolution reconstruction (SRR) technology can improve image spatial resolution with existing imaging systems. Total variation regularization method is one of the SRR methods. In bilateral total variation regularization method (BTV) proposed by Farsiu, the scale weight is a constant, so the image reconstruction effect is not ideal for texture and edge region. In order to solve this problem, an adaptive weighted regularization function and regularization parameter algorithm is proposed in this paper. In the proposed algorithm, the image local structure information is used to control the shape, bandwidth of the weighted function and the regularization parameter. The experimental results show that the proposed algorithm, compared with BTV, can retain the image details better and improve the image contrast.

9217-77, Session PMon

Machine vision based on the concept of contrast sensitivity of the human eye

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In this work we pursued a goal to develop a model of the contrast sensitivity function (CSF) of a machine vision system, based on the CSF of the human visual system. By analogy with the human eye, we introduced the concept of ganglion cells and receptive fields to the artificial light-sensitive elements. By further following this concept, we introduced quantative measures of local and global contrast of the digital image. We suggested that the contrast sensitivity threshold forms an isoline in the parameter space contrast - spatial frequency. The model, implemented in a computer vision system, has been compared to the results of contrast sensitivity research, conducted directly with the human visual system, and demonstrated a good match. The results of our research can be used to improve the performance of machine vision and technical imaging systems.

9217-78, Session PMon

Image reconstruction in speckle interferometry

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Speckle imaging technique is one of the several effective methods, which can overcome atmosphere turbulence effects and obtain diffraction-limited resolution of objects. It is achieved by the integration of a series of short-exposure images of the object.

This paper is the part of a series dedicated to the speckle imaging of binary stars carried out by the research team of Shanghai Astronomical Observatory. The observation experiments were carried out from 2010 to 2012 with 1.56-m telescope using a speckle camera, and the high resolution image were reconstructed successfully.

In this paper, we mainly concerned speckle interferometry and iterative shift-and-add. Speckle interferometry was proposed by Labeyrie in 1970, the information obtained in this manner is not easily interpreted because the final output after processing is the autocorrelation of the object. This technique has been widely used in the observational astronomy, especially in binary stars. Iterative Shift-and-Add is working in spatial domain, the complex Fourier phase recover is avoided in this method and the data processing become much easier.

As we know, speckle imaging algorithm needs to deal thousands of images, and the high computational complexity brings a lot of problems. Modern GPUs are very efficient at manipulating computer graphics, and their highly parallel structure makes them more effective than general-purpose CPUs for algorithms where processing of large blocks of data

is done in parallel. So we proposed a reconstruction software based on CUDA architecture, compared with C++ program based on CPU, the speed ratio can reach 10 times.

9217-79, Session PMon

Accuracy evaluation of segmentation for high resolution imagery and 3D laser point cloud data

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High resolution satellite imagery and 3D laser point cloud data provide precise geometry, rich spectral information and clear texture of feature. The segmentation of high resolution remote sensing images and 3D laser point cloud is the basis of object-oriented remote sensing image analysis, for the segmentation results will directly influence the accuracy of subsequent analysis and discrimination. Currently, there still lacks a common segmentation theory to support these algorithms. So when we face a specific problem, we should determine applicability of the segmentation method through segmentation accuracy assessment, and then determine an optimal segmentation. To today, the most common method for evaluating the effectiveness of a segmentation method is subjective evaluation and supervised evaluation. For providing a more objective evaluation result, we have carried out following work. Analysis and comparison previous proposed image segmentation and segmentation accuracy evaluation methods, which is area-based metrics, location- based metrics and combinations metric. 3D point cloud data, which was gathered by Reigl VZ1000, was used to make two-dimensional transformation of point cloud data. The object-oriented segmentation result of farms, buildings and farmland polygons were was used as test object and adopted to evaluate segmentation accuracy.

9217-80, Session PMon

MODIS images super-resolution algorithm via sparse representation

Yue Pang, Lingjia Gu, Ruizhi Ren, Jian Sun, Jilin Univ. (China)

Spatial resolution of remote sensing image is a very important factor for target recognition and precision interpretation. Considering the limited number of low-resolution remote sensing images and the cost problem, a learning-based super-resolution algorithm is introduced, which can increase the spatial resolution of MODIS remote sensing images under the current hardware condition of the imaging system.

Super-Resolution is an image enhancement technique that generates one or more high-resolution images from one or more low-resolution observations of the same scenario. The proposed learning-based super-resolution algorithm can obtain the prior knowledge from the training database, which fully takes advantage of knowledge of the image itself. The basic idea behind the algorithm is to acquire the relationship between high-resolution Landsat TM image and low-resolution MODIS image by using the learning model, further give the instruction for reconstructing a high-resolution MODIS image. Feature extraction and learning model are two vital parts included in this algorithm.

Based on the current mainstream algorithms, an effective algorithm of learning-based super-resolution is proposed in the paper. The proposed algorithm takes into account both the quality of reconstruction and computation efficiency, which can build a more effectual learning model and provide more complete prior knowledge. Meanwhile, the algorithm enhances the training speed of learning and decreases the amount of computation. The experimental results demonstrate the effectiveness of the proposed algorithm.

9217-81, Session PMon

A study on an automatic Ronchi test system

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In recent years, the glasses had gradually been personal accessory to human life, so the demand of various types of glasses has increased significantly, especially safe glasses and sunglasses. And the requirement of full-inspection of the lens of safe glasses and sunglasses are getting seriously. In the past, the fast lens optical quality inspection were performed by Ronchi test and the Ronchigram images were observed and judged by human eyes. However, the larger uncertainty of measurement will be induced while observing the Ronchi patterns using human eyes. Therefore, this study presents the development of an automatic lens Inspection Instrument based on Ronchi tester, which comprises of the machine vision, image analysis and processing method without human operation involved. In addition, an optical quality index based on Ronchigram has beendeveloped so as to classify the quality of test lens.

9217-82, Session PMon

Relay-and-antenna selection and digital transceiver design for two-way AF-MIMO multiple-relay systems

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In the paper, joint optimization of precoders and equalizers for terminal sides and amplifying matrices for multiple relays is proposed for a two-way amplify-and-forward (AF) multiple-input multiple-output (MIMO) multiple-relay system with correlated channel uncertainties. Terminal transceivers and multiple relaying precoding matrices with the use of relay antenna subset selection are jointly designed based on the minimum mean square error (MMSE) criterion when terminals fail to erase the self-interference completely owing to lack of precise correlated channel state information (CSI). This optimization problem of beamforming and precoding matrices under power constraints belong to neither concave nor convex so that an iterative nonlinear matrix-form conjugate gradient (MCG) search algorithm is applied to explore the local optimal solution. In addition, this paper investigates three antenna subset selection algorithms at relay nodes and their related performance analysis. Simulations are conducted to illustrate that the robust transceiver joint design architecture for an AF-MIMO two-way system equipped with multiple relays substantially outperforms a non-robust transceiver design that assumes estimated channels as actual channels. Moreover, simulations are conducted to compare the system performance of the proposed transceiver joint design with other existing transceiver design techniques for a two-way AF-MIMO multiple-relay system with the use of antenna subset selection schemes under correlated channel uncertainties.

9217-83, Session PMon

Application of subsidence monitoring over Yangtze river marshland with ground-based SAR system IBIS

Zhiwei Qiu, Hohai Univ. (China)

The subsidence was monitored by micro-deformation monitoring system IBIS based on ground-based SAR interferometry technology. The displacement in the line of sight value can be rectified to the subsidence direction after corrected the atmospheric disturbance, then get continuous deformation map of observation area in 24 hours. These experiments show that the Ground-Based InSAR technology can be

applied to ground subsidence monitoring in millimeter precision, and dynamic monitoring of micro deformation.

9217-85, Session PMon

Objective evaluation of naturalness, contrast, and colorfulness of tone-mapped images

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The main obstacle preventing High Dynamic Range (HDR) imaging from becoming standard in image and video processing industry is the challenge of displaying the content. The prices of HDR screens are still too high for ordinary customers. During last decade, a lot of effort has been dedicated to finding ways to compress the dynamic range for legacy displays with simultaneous preservation of details in highlights and shadows which cannot be achieved by standard systems. These dynamic range compression techniques are called tone-mapping operators (TMO) and introduce novel distortions such as spatially non-linear distortion of contrast or naturalness corruption. This paper provides an analysis of objective no-reference naturalness, contrast and colorfulness measures in the context of tone-mapped images evaluation. Reliable measures of these features could be further merged together into single overall quality metric. The main goal of the paper is to identify the potential candidates for such a combination.

9217-19, Session 3

Analysis of prediction algorithms for residual compression in a lossy to lossless scalable video coding system based on HEVC

Andreas Heindel, Eugen Wige, André Kaup, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Lossless compression of image and video content is desired in many professional applications like medical imaging, surveillance systems, and archiving systems. However, a lossless representation usually requires much more storage capacity compared to lossy compression. There are scenarios where it is not practical or even infeasible to handle the huge amount of data for lossless coding. In these cases a lossy version of the data for preview purposes would be favorable. Furthermore it may be required to improve the lossy preview to lossless quality in a second step. In order to fulfill all these demands we investigate a very flexible and low-complex scalable video coding scheme with a lossy base layer compressed using HEVC.

In this contribution we examine different spatial prediction algorithms for lossless coding of the enhancement layer. Starting with the lossy coded base layer, residual images are computed by subtracting the reconstructed pictures from the original ones. Subsequently, each residual image is losslessly compressed by means of spatial prediction and entropy coding. For entropy coding we employ CABAC, which is already included in the HEVC framework. Intra prediction using Sample-based Weighted Prediction (SWP) has already delivered good compression results in [1]. However, it turned out that SWP is not always the optimal prediction scheme. Therefore, in this paper we compare the compression performance of SWP to other well established prediction methods as least-squares prediction and the LOCO-I algorithm. Due to the fact that the residual images can be considered to be extremely noisy, the performance of the examined algorithms cannot be deduced from other studies based on usual images.

[1] A. Heindel, E. Wige, and A. Kaup, “Sample-based Weighted Prediction for Lossless Enhancement Layer Coding in HEVC”, Picture Coding Symposium (PCS), Grand Compression Challenge, San José, 2013

9217-20, Session 3

A linearly constrained signal subspace projection for target detection in hyperspectral images

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The hyperspectral images have been widely applied to target detection. Generally, the target signatures should be known a priori for filter-based detection methods. However, the uncertainty of target signatures caused by the influence of atmosphere interference or other random noise degrades detection performance. Thus, developing a robust detection method is important in hyperspectral image analysis.

In the study, we propose a linearly constrained signal subspace projection (SSP) approach to target detection. Instead of using single constraint on target detection, we design an optimal filter with multiple constraints on desired targets by using SSP. The proposed SSP approach fully exploits the orthogonal property of two orthogonal subspaces: one denoted signal subspace containing desired and undesired/background targets; the other denoted noise subspace, which is orthogonal to signal subspace. By projecting the weights of the detection filter on the signal subspace, the proposed SSP can reduces some estimation errors in target signatures and alleviate the performance degradation caused by uncertainty of target signature. The SSP approach can detect desired targets, suppress undesired targets and minimize the interference effects. In experiments, we provide three methods in selecting multiple constraints of the desired target: K-means, principal eigenvectors and endmenber extracting techniques. Simulation results show that the proposed SSP with multiple constraints selected by K-means has better detection performance. Furthermore, the proposed SSP with multiple constraints is a robust detection approach which could overcome the uncertainty of desired target signature in real image data.

9217-21, Session 3

Method of automatic color rendering settings for machine vision systems

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Today machine vision systems (MVS) are widely used to solve various problems of observation and control in science and technology, and industrial applications. Generally a color rendering of such systems is sufficient for visual inspection of the process on the screen. However, there is a problem of MVS color rendering settings when you need to measure the exact color coordinates of the analyzed object at each point of its surface image in automatic mode.

Paper presents results of the development of specialized method for MVS color rendering settings. Using this method can provide the required accuracy of the color analysis of the observed object. The algorithm for automatic setting of color rendering and software implementing it were developed. An experimental study of the algorithm in a variety of lighting conditions and with a few different MVS were carried out.

The concept of the proposed method is to create a transformed MVS color space based on values of “reference colors”. These colors are the colors of certified test table. Knowing the error in determining the color coordinates for at least four colors of the test table, you can convert them and all other points between them in the color space in order to minimize the overall error in determining the color by MVS.

The accuracy of this method depends on the distance between “reference colors” in the color space. Thereby it is possible to set MVS for accurate color measurement if you have test table with sufficiently large range of colors.

Such approach is very resource-intensive, but in the long run, it gives an accurate result for all colors and shades of image or video. Additive color

model RGB is used to construct the transformed color space, because this model is the most convenient for color reproduction.

9217-22, Session 3

Energy minimization of mobile video devices with a hardware H.264/AVC encoder based on energy-rate-distortion opmization

Donghun Kang, Jungeon Lee, Chul-Hee Lee, Chong-Min Kyung, Jongpil Jung, KAIST (Korea, Republic of)

Along with growing interest in security, the demand for mobile surveillance cameras also grows. In mobile video systems powered by battery, reducing the encoder's compression energy consumption is critical to prolong its lifetime. During the development of codec standards in last two decades, many groups studied rate and distortion optimization (RDO) for encoders' compression efficiency. However, this RDO efforts is not enough for mobile video systems because energy constraint has become a dominant issue beyond the rate and distortion constraints. Over these works, energy-rate-distortion (E-R-D) optimization methods provide extra energy saving. Previous energy-rate-distortion optimization methods based on a software codec is not suitable for practical mobile camera systems because the energy consumption is too large and encoding rate is too low. In this paper, we propose an E-R-D model for the hardware codec based on the gate-level simulation framework to measure the switching activity and the energy consumption. Our power consumption model consider not only encoder's operation with SRAM but also DRAM which takes most of power consumption in hardware design. From the proposed E-R-D model, an energy minimizing algorithm for mobile video camera sensor have been developed with the G-O-P size and QP as run-time control variables. Our experimental results show that the proposed algorithm provides to 34.38% of energy consumption while satisfying the rate and distortion constraints.

9217-24, Session 3

Joint-layer encoder optimization for HEVC scalable extensions

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Scalable video coding is one of the most common technologies to support video playback on heterogeneous devices with varying channel conditions. To improve enhancement layer coding performance, inter-layer prediction is used. In HEVC scalable extensions (SHVC), inter layer prediction is achieved by using the collocated base layer picture as an additional reference picture for coding of the current enhancement layer picture. Joint-layer optimization methods have been previously proposed to jointly consider the rate-distortion optimization (RDO) processes in the base and enhancement layers and to balance the coding mode selection in each layer. However, such existing joint-layer optimization methods are difficult to be directly extended to the SHVC encoder, mainly due to complicated Coding Unit (CU) and Prediction Unit (PU) splitting decisions in HEVC. To solve these problems, a novel joint-layer optimization method is developed by adjusting QP at the CTU level to optimally allocate the rate-distortion resource between the two layers. To decide the video quality that the end user receives, the proposed method calculates a combined PSNR by considering the packet loss rate of base and enhancement layer video packets and uses the combined PSNR as the distortion metric. The QP values of those base layer CTUs referenced by the enhancement layer are decreased, and the QP values of the non-reference CTUs are increased. Finally the QP value with minimal joint-layer RD cost is selected. Simulation results show that the proposed method can achieve average coding performance improvement of 1% compared to the SHVC reference software.

9217-25, Session 3

Source coding for transmission of reconstructed dynamic geometry: a rate-distortion-complexity analysis of different approaches

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In this paper we discuss geometry compression in the context of 3D Tele-Immersion, where 3D geometry is reconstructed from one or more depth cameras and transmitted interactively. As this reconstruction process can be distributed between sender and receiver, various compressed representations (coded depth images, compresed point cloud, compressed 3D mesh, compresed mesh snapshot) can be exchanged between sender and receiver resulting in a different rate-distortion-complexity. In this paper we apply state of art tools to compare the rate-time-complexity of transmitting reconstructed mesh geometry. First, we introduce two different reconstruction datasets. The first dataset/system directly reconstructs the surface, resulting in time-varying geometry data where both connectivity and geometry changes over time. The second dataset is taken from a recontruction system that uses a shape based template fitting approach with a pre-register template, resulting in time-consistent mesh data. We compare the achieved rate-distortion-complexity between codecs developed in MPEG-4 recently to octree based point cloud coding with a re-triangulation at the receiver. The results show that octree based compression of the time-varying mesh data can achieve a much lower bit-rate and complexity compared to MPEG-4, but larger distortions. Also, re-triangulation at the receiver can be problematic. On the contrary, for the second time-consistent mesh dataset the MPEG-4 tools outperform octree compression with xor prediction achieving lower distortion and lower rate. Lastly, we compare methods for exploiting temporal correlation between time-varying mesh data and introduce a new method for inter-frame prediction based on octree voxel correspondance that achieves significant bit-saving in dataset 1.

9217-26, Session 3

Research on test of product based on spatial sampling criteria and variable step sampling mechanism

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This paper proposes an effective approach for online testing the assembly structures inside products using multiple views technique and X-ray digital radiography system based on spatial sampling criteria and variable step sampling mechanism. Although there are some objects inside one product to be tested, there must be a maximal rotary step for an object within which the least structural size to be tested is ascertained in advance. In offline learning process, Rotating the object by the step and imaging it and so on until a complete cycle is completed, an image sequence is obtained that includes the full structural information for recognition. The maximal rotary step is restricted by the least structural size and the resolution of the imaging system. During online detection stage, in order to achieve the detection of the structural quality for complicated products accurately and rapidly, the program finds the optimum solutions to all different target parts in the sequence with SIFT algorithm and bisearch method and carries out exactness image matching with correlation coefficient weighted of multi-character via Bayes decision. Aiming at the issue of some objects may be occluded by others in a scene, the paper adopts variable step-size sampling mechanism to rotate the product specific angles with different steps according to different objects inside the product and re-match. The experimental results show that the variable step-size method can save an average of 4.14s than the traditional fixed-step detection method.

9217-84, Session 3

Comparative assessment of H.265/MPEG-HEVC, VP9, and H.264/MPEG-AVC encoders for low-delay video applications

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The popularity of low-delay video applications dramatically increased over the last years due to a rising demand for real-time video content (such as video conferencing or video surveillance), and also due to the increasing availability of relatively inexpensive heterogeneous devices (such as smartphones and tablets). To this end, this work presents a comparative assessment of the two latest video coding standards: H.265/MPEG-HEVC (High- Efficiency Video Coding), H.264/MPEG-AVC (Advanced Video Coding), and also of the VP9 proprietary video coding scheme. For evaluating H.264/MPEG-AVC, an open-source x264 encoder was selected, which has a multi-pass encoding mode, similarly to VP9. According to experimental results, which were obtained by using similar low-delay configurations for all three examined representative encoders, it was observed that H.265/MPEGHEVC provides significant average bit-rate savings of 32.5%, and 40.8%, relative to VP9 and x264 for the 1-pass encoding, and average bit-rate savings of 32.6%, and 42.2% for the 2-pass encoding, respectively. On the other hand, compared to the x264 encoder, typical low-delay encoding times of the VP9 encoder, are about 2,000 times higher for the 1-pass encoding, and are about 400 times higher for the 2-pass encoding.

9217-27, Session 4

Comparison of compression efficiency between HEVC/H.265 and VP9 based on subjective assessments

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No Abstract Available

9217-28, Session 4

Statistical feature selection for enhanced detection of brain tumor

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Feature-based methods are widely used in the brain tumor recognition system. Robust of early cancer detection is one of the most powerful image processing tools. Specifically, statistical features, such as geometric mean, harmonic mean, mean excluding outliers, median, percentiles, skewness and kurtosis, have been extracted from brain tumor glioma to aid in discriminating the level I from level II using fluid attenuated inversion recovery sequence in the diagnosis of brain tumor. Statistical feature describes the major characteristics of each level from glioma which is an important step to evaluate non-heterogeneity of cancer area pixels. In this paper, we address the task of feature selection to identify the relevant subset of features in the statistical domain, while discarding those that are either redundant or confusing, thereby improving the performance of feature-based scheme to distinguish between level I and level II. We apply a Decision Structure algorithm to find the optimal combination of non-homogeneity based statistical features for the problem at hand. We employ a Naïve Bayes classifier to evaluate the performance of the optimal statistical feature based scheme in terms of its glioma level I and level II discrimination capability and use real-data collected from 17 patients have a brain tumor. Dataset provided from 3 Tesla MR imaging system by MD Anderson Cancer Center. For the specific data analyzed, it is shown that the identified dominant features yield higher classification accuracy, with lower number of false alarms and missed detections, compared to the full statistical based feature set. This work has been proposed and analyzed specific glioma types which level I and level II and the dominant features were considered as feature aid to prognostic indicators. These features were selected automatically to be better able to determine prognosis from classical imaging studies.

9217-29, Session 4

Robust features encoded limited physiological information for face recognition

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Face recognition is considered as one of the most dynamic and complex research areas in machine vision and pattern recognition due to the variable appearance of face images. Changes in appearance may occur due to many factors, such as facial attributes compatibility complexity, the motion of face parts, facial expression, pose, illumination and partly occlusion. As a result face recognition problem become ill-posed.

This paper proposes a local feature based face recognition technique which makes use of dynamic (mouth) and static (eyes, nose) salient features as limited physiological information of face obtained through SURF descriptor. SURF (Speeded up robust features) descriptor is a robust image descriptor. It can be used in computer vision tasks like object recognition or 3D reconstruction. It is known as the improved version of the SIFT (Scale Invariant Feature Transform) descriptor. The standard version of SURF is several times faster than SIFT and more robust against different image transformations than SIFT. SURF is based on sums of 2D Haar wavelet responses and makes an efficient use of integral images. As basic image features it uses a Haar wavelet approximation of the determinant of Hessian blob detector.

Differences in facial expression, head pose, illumination, and partly occlusion may result to variations of facial characteristics and attributes. To capture the face variations, face characteristics of dynamic and static parts are further fused by concatenation with the detected SURF interest points extracted from localized mouth, eyes and nose facial parts. The proposed technique has made an attempt to handle this problem.

It has been determined that when the face matching accomplishes with the whole face region, the global features (whole face) are easy to capture and they are generally less discriminative than localized features. In the proposed face recognition method, local facial landmarks are considered for further processing. The optimal face representation using SURF descriptor on local landmarks then allows matching the localized facial features efficiently.

It first detects and extracts automatically some salient facial parts such as eyes, mouth and nose with the help of some standard facial landmark detection algorithms. Scale and rotation Invariant SURF feature descriptor is then used on each of these facial parts to determine interest points and finally fusion of SURF interest points are performed. For Matching between two faces is accomplished by considering distance metrics with the pair of corresponding fused feature vectors. These matching scores obtained from verification module are then further characterized by Doddington's user-dependent matcher reliability method. The relevance of individual matchers towards more efficient and robust performance is determined by wolf and lamb factors. It has been estimated that, both these factors can decrease the performance of any biometric system by accepting more and more imposters as false accept. In Doddington's concept, for user weighting, the users who can imitated labeled as lambs, i.e., imposters can provide biometric cues that are similar to that of lambs. Wolves on the other hand can successfully imitate some other users. The proposed techniques are evaluated against three face databases, namely, FERET, ORL, BANCA and IITK face databases.

9217-30, Session 4

3D live meshes of natural objects and scenes

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This paper presents a review of the current status of the 3D object acquisition of live natural objects in real-time and the impact of the quality of the acquired object on the compression performance. The 3D object and scene acquisition technology is becoming available on mobile devices with specialized hardware as well as on general purpose devices due to the advances in computer vision and the point cloud processing. There is comparing of the methods for 3D object live meshes and dynamic scene reconstruction.

9217-31, Session 4

The distribution for foggy drop size based on image analyzing

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An Investigation of Fog Water Droplet Structure Characteristics Based on Image Analysis Fog is a natural phenomena, which is a collection of liquid water droplets congealed by saturated vapor over condensation nuclei (such as dust, particle, gem etc) when the surface temperature drops. At autumn and winter, because of the temperature inversion caused by surface radiation, fog often happens. However, in the river such as the Three Gorges, or in the motorway near the river, local fog often happens at all seasons. Because of low visibility in the foggy weather, it is difficult for people to go outside, and this weather also increases the potentiality of safety issues in the highway and waterway transportation. The fog density is closely related to the visibility. In the light propagation, the refraction by small water droplets in the fog causes the mistiness of the target objects. Therefore, in order to effectively refine the misty images, it is necessary to analyze the composition and the structure characteristics of the water droplets. By analyzing the relationship among droplet structure, visibility and fog water content, and analyzing the degradation degree of two points with different depth in the misty image, this paper approximates visibility and water content based on the atmospheric degradation model. Furthermore, this paper also approximates the parameters of the droplet structure distribution function.

9217-32, Session 4

Efficient object recognition algorithms for telescopes

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When using a telescope to observe or search a non-stellar object with or without predicted position information, we need to recognize it in the field of view (FOV) firstly. For a robotic telescope for that kind of purposes, we must do it automatically by image processing instead of a human brain. If the target is the only object in the FOV, it would be easy to recognize it using connected components detection algorithm. But a telescope with large FOV tends to produce an image including tens of background stars as well as the target object. Long exposure images distinguish a non-stellar object from the stellar ones, but a very short exposure image by a fast frame rate camera cannot tell the difference between them. The large FOV and the use of fast frame rate camera are very common for a telescope for searching and guiding purposes, in which case, we need to united several consecutive frames to achieve the goal. This article introduces an algorithm to do so effectively and efficiently. We firstly stack the consecutive frames with FIFO queue in a very efficient way. For a typical 30 FPS camera, stacking 60 frames won't slow down the FPS with a mainstream computer. The more frames are stacked, the easier the programs tell the difference between the object and stars, and more image noises can be averaged. And the dynamic servo tracking performance does not have to be sacrificed. After that, we perform connected components detection with several methods, making a trade-off between effectiveness and efficiency. We realize it with c++ and a popular real time computer vision library OpenCV, taking advantage of some of its new GPU-accelerated module features.

9217-33, Session 4

Facial recognition using composite correlation filters designed by multiobjective combinatorial optimization

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Facial recognition is a difficult task due to variations in pose and facial expressions, as well as presence of noise and clutter in captured face images. In this work, we address facial recognition by means of composite correlation filters designed with multi-objective combinatorial optimization. Given a large set of available face images having variations in pose, gesticulations, and global illumination, a proposed algorithm synthesizes composite correlation filters by optimization of several performance criteria. The resultant filters are able to reliably detect and correctly classify face images of different subjects even when they are corrupted with additive noise and nonhomogeneous illumination. Computer simulation results obtained with the proposed approach are presented and discussed in terms of efficiency in face detection and reliability of facial classification. These results are also compared with those obtained with existing composite filters.

9217-34, Session 4

Multispectral palmprint recognition by Kernel associative memory-based computational model and finite ridgelet transform

Dakshina R. Kisku, Asansol Engineering College (India); Phalguni Gupta, Indian Institute of Technology Kanpur (India); Jamuna Kanta Sing, Jadavpur Univ. (India)

Due to low-cost, user-friendly and reliable one, palmprint recognition has been established itself a very accurate solution for a range of access control applications and identity verifications. Several studies on palmprint recognition have been made for improving performance of the system by palmprint images taken under visible light. However, in the last few years, thrust for robust palmprint system has begun with multispectral palm images. These multispectral palm images which are captured under visible and infrared light with different wavelengths show best substitution of visible ones by improving system performance further with very little error rates.

In this paper, we advocate a hierarchical kernel associative memory (KAM) based computational model for robust multispectral palmprint recognition with finite Ridgelet transform representation. To characterize multispectral palmprint image, Finite Ridgelet Transform is used to achieve a very compact representation of linear singularities and the FRIT captures the singularities along lines and edges. Finite Ridgelet Transform is used to represent the multispectral palmprint image and it is then modeled by Kernel Associative Memories. Finally recognition scheme is thoroughly tested with a benchmarking multispectral palmprint database CASIA. For recognition purpose Bayesian classifier is used. The experimental results exhibit robustness of the proposed system under different wavelengths.

9217-35, Session 5

Reconstruction of compressive multispectral sensing data using a multilayered conditional random field approach

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The prevalence of compressive sensing is continually growing in all facets of imaging science. Compressive sensing allows for the capture and reconstruction of an entire signal from a sparse (under-sampled), yet sufficient, set of measurements that is representative of the target being observed. This compressive sensing strategy reduces the duration of the data capture, the size of the acquired data, and the cost of the imaging hardware as well as complexity while preserving the necessary underlying information. Compressive sensing systems require the accompaniment of advanced reconstruction algorithms to reconstruct complete signals from the sparse measurements made. Here, a new reconstruction algorithm is introduced specifically for the reconstruction of compressive multispectral sensing data that allows for high-quality reconstruction from acquisitions at sub-Nyquist rates. We propose a multi-layered conditional random field (MCRF) model, which extends upon the CRF model by incorporating two joint layers of certainty and estimated states. The proposed algorithm treats the reconstruction of each spectral channel as a MCRF given the sparse multispectral measurements. Since the observations are incomplete, the MCRF incorporates an extra layer determining the certainty of the measurements. The proposed MCRF approach was evaluated using compressive multispectral data acquisitions, and is shown to enable fast acquisition of multispectral sensing data with reduced imaging hardware cost and complexity.

9217-36, Session 5

Correction of defective pixels for medical and space imagers based on Ising theory

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A novel model for image restoration based on Ising theory [1,2] is discussed where the imagers are:

(i) Digital Cameras in space damaged from cosmic radiation. Like all microelectronic devices, digital imagers are prone to develop defects over their lifetime. The most common type of defect is “hot pixel”, i.e. a pixel that appears as a bright dot in every image. With many imagers located in remote, unreachable locations such as space, automatic detection and correction of defects are crucial [3,4].

(ii) Ultrasonic medical devices damaged from speckle noise. Speckle noise appears as a multiplicative granular noise due to the random interference of the wavelets scattered by the microscopic fluctuations of the object surface within one resolution element. The presence of speckle noise in ultrasound images reduces the resolution of the image and the effectiveness of image interpretation.

In previous works [5-7] we have suggested a simulated annealing algorithm [8,9] based on Ising theory for the restoration of colored images and videos which were damaged from various kinds of noise. In what follows we will use an improved and adjusted version of this algorithm (based on Tsallis distribution [10] and quantum annealing [11]) for solving the above problems. The new algorithm is suited for automatic noise estimation and appropriate choice of the model’s parameters.

We will present restoration results which are achieved by the combination of known algorithms such as Median and LOCO-I [12] together with our Ising-like model. The PSNR and SSIM values of the restored images will be shown to exceed the values achieved with similar methods.

Summary:

A simulated annealing model based on Ising Theory and well-known filters was suggested for the restoration damaged pixels in space and medical imagers. By estimating the noise and activity in each neighborhood, we were be able to automatically adjust the model’s parameters for handling different tasks. Restoration of hot pixels showed significant improvement of the damaged images. Our results are close to the ones in [8,9] but we used only the damaged image and did not use dark current information. Restoration of ultra-sound images has also outperformed other filters, although with much higher complexity.

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9217-37, Session 5

Estimation of grain size in asphalt samples using digital image analysis

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Asphalt is made of a mixture of stones of different sizes and a binder called bitumen, the size distribution of the stones is determined by the recipe of the asphalt. One quality check of asphalt is to see if the real size distribution of asphalt samples is consistent with the recipe. This is usually done by first extracting the binder using methylenchloride and then sieving the stones to see how much that pass every sieve size. Methylenchloride is highly toxic and it is desirable to find the size distribution in some other way. In this paper we find the size distribution by slicing up the asphalt sample and using image analysis techniques to analyze the cross-sections. First the stones are segmented from the background, bitumen. This is done with a fast marching algorithm, where the curve starts in some very dark areas in the bitumen and propagates fast in dark areas and slower in the lighter parts. Then some morphological operations are performed to separate some segments that were wrongly segmented. After this rectangles are fit to the detected stones by using a two steps approach to first estimate the orientation of the segment and then fit a rectangle to it. We then estimate the sizes of the stones by using the width of the rectangle. The result is compared with both the recipe for the asphalt and with the result from the standard analysis method, and our method shows good correlation with those.

9217-38, Session 5

Interactive alignment and image reconstruction for wafer-level multi-aperture camera systems

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In multi-view camera setups, resolution can be improved by interlacing the images of adjacent cameras where their fields of view overlap. Precise knowledge of the camera parameters is crucial to achieve artifact-free and high-resolution image reconstruction. This knowledge is usually obtained by calibrating each multi-camera system individually.

When individual cameras are replaced by a monolithic multi-aperture camera on wafer level, all optical channels are placed on the same stack of glass and silicon substrates. Therefore, neighboring lens or sensor elements in each layer are aligned with lithographic precision. This improves prior knowledge about the viewing direction and geometric distortion of the individual channels. In principle, channels can be recombined into a complete image by only using design data. Calibration of individual camera systems can be avoided.

This is only true, however, if the parts of the camera system are aligned with sufficient precision. Especially the alignment of the optics stack to the image sensor is critical. Misalignment such as rotation or wedge error between sensor and optics causes artifacts in parts of the reconstructed image.

Fortunately, alignment of sensor and optics only has six degrees of freedom, which makes description and correction of misalignment relatively simple. This is true even for a large number of optical channels, as they are located together on a rigid glass substrate.

We demonstrate a system for interactively previewing and correcting the effects of misalignments along these six axes, using geometric transformations of the channel images. This way, we can track systematic alignment errors during assembly. We also compare images from a properly aligned system, reconstructed with just design data, to images reconstructed with calibration data.

9217-39, Session 5

Automatic inspection of solar wafer by NIR imaging with backlight illumination strategy

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One of the most important procedures in the production of solar wafers is the inspection and identification of defects. Chief among them is the micro-crack which is caused by the mechanical loads or heat effects during wafer processing. The problem is very challenging because this type of defect is very small and completely invisible to naked eyes. The presence of other heterogeneities like grainy materials and broken metal fingers in solar wafer further complicates the problem. In this paper, an efficient solar wafer machine inspection system utilising near infrared radiation and advanced image processing algorithm has been developed and tested. In operation the wafer is illuminated by an array of Infrared Light Emitting Diode (IR-LED), and the image is captured using the Goldeye P-008 NIR camera with spectral sensitivity from 900-1700 nm. An improved version of the Niblack's algorithm has been developed to detect and characterize various forms of micro-crack defects in NIR image. In summary the new algorithm works by first calculating the Niblack's operator, and second, adaptively segmenting the image based on its gradient and standard deviation values. The performance of the new algorithm is compared with existing segmentation algorithms and results presented.

9217-40, Session 5

Target tracking using interest point detection and correlation filtering

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A reliable method for real-time target tracking is presented. The method utilizes an interest point detector and a bank of locally adaptive correlation filters. The point detector is used to identify local regions in the observed scene with the potential location of a target. Next, the bank of correlation filters is employed to reliable detect the target and to accurately estimate the position and orientation of the target within the scene, by processing local regions of the scene identified by the detector. Using information of past state estimates of the target the proposed method predicts the state of the target in next frame in order to perform fast and accurate target tracking by focussing signal processing only on small regions of the scene and by modifying the number of required correlation filters of the bank in each observed frame. In order to achieve a real-time operation performance the proposed method is implemented in a Graphics Processing Unit (GPU) exploiting massive parallelism. Computer simulations results obtained with the proposed method are presented, discussed, and compared with those results obtained with similar state-of-the-art target tracking methods. The performance of the proposed method in real scenes is also presented and discussed.

9217-41, Session 5

An algorithm for the characterization of digital images of pigmented lesions of human skin

Laura Y. Mera-González, José A. Delgado Atencio, Juan Carlos Valdiviezo-Navarro, Margarita Cunill-Rodriguez, Univ. Politécnica de Tulancingo (Mexico)

Melanoma is the most deadly form of skin cancer in human in all over the world with an increase number of victims yearly. One traditional form of diagnosis melanoma is by using the so called ABCDE rule which stands for Asymmetry, Border, Color, Diameter and Evolution of the lesion. For melanoma lesions, the color as a descriptor exhibits heterogeneous values, ranging from light brown to dark brown (sometimes blue reddish or even white). Therefore, investigating on color features from digital melanoma images could provide insights for developing automated algorithms for melanoma discrimination from common nevus. In this research work, an algorithm is proposed and tested to characterize the color in a pigmented lesion. The developed algorithm measures the hue of different sites in the same pigmented area from a digital image using the HSI color space. The algorithm was applied to 50 digital images of unequivocal melanomas and 50 images of common nevus, which were taken from several data bases. Preliminary results indicate that visible color changes of melanoma sites are well accounted by the proposed algorithm. Other factors, such as quality of images and the influence of the shiny areas on the results obtained with the proposed algorithm are discussed.

9217-42, Session 6

On the integer coding profile of JPEG XT

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JPEG XT (ISO/IEC 18477-1), the latest standardization initiative ofthe JPEG committee (ISO SC29WG1) defines an image compression standard backwards compatible to the well-known JPEG standard (ISO/IEC 10918-1). JPEG XT extends JPEG by features like HDR image compression, lossless compression that is compatible to the DCT modes of JPEG, and representation and compression of alpha channels.

In this work, the author presents a profile of JPEG XT that, while offering

both lossy and lossless compression of HDR images, is especially suited for hardware implementations by requiring only integer logic. All functional blocks of a JPEG XT codec are here implemented by fixed point logic whose design and bit assignment are discussed in the paper. A performance analysis and comparison with other profiles of JPEG XT concludes the work.

9217-43, Session 6

Nonlinear multi-scale complex wavelet diffusion based speckle reduction approach for 3D ultrasound images

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3D ultrasound imaging has advantages as a non-invasive measurement technique, and a faster examination procedure that can display volume information in real time. However, its resolution is affected due to the presence of speckle noise. Speckle is a kind of granular noise which arises from diffusive scattering and interference and limits the quality of ultrasound images. Speckle noise is currently the main shortcoming of ultrasound imaging and its reduction is essential in providing better clinical diagnoses. The reduction of speckle noise whilst preserving important anatomical features are seemingly opposing goals in ultrasound imaging. In this paper, we introduce a nonlinear multi-scale complex wavelet diffusion based algorithm for 3D ultrasound images. The proposed method tries to improve volume visualization of 3D ultrasound images, and enhance the accuracy of volume determination considering some useful features of the dual tree complex wavelet transform and nonlinear diffusion. Using the proposed algorithm, speckle noise is suppressed whilst sharp edges are preserved without degrading the anatomical features by applying iterative multi-scale diffusion on the wavelet coefficients. The proposed algorithm is validated using synthetic, real phantom and clinical 3D images. Experimental results demonstrate that the proposed algorithm significantly reduces speckle noise while preserving sharp edges without discernible distortions. The proposed algorithm performs better than the existing approaches in both qualitative and standard quantitative measures, such as Figure of merit (FoM), structure similarity (SSIM), contrast to noise ratio (CNR), peak signal to noise ratio (PSNR), and universal image quality indices (UIQI).

9217-44, Session 6

To develop a geometric matching method for precision mold alignment machine

Chun-Jen Chen, National Formosa Univ. (Taiwan); Chun-Li Chang, Instrument Technology Research Ctr. (Taiwan); Wen-Yuh Jywe, National Formosa Univ. (Taiwan)

In order to develop a high accuracy optical alignment system for precision molding machine, a geometric matching method was developed in this paper. The alignment system includes 4 high magnification lenses, 4 CCD cameras and 4 LED light sources. In the precision molding machine, a bottom metal mold and a top glass mold are used to produce a micro lens. The two molds combination does not use any pin or alignment part. They only use the optical alignment system to alignment. Because the working distance of lens is short, the off-axis alignment method was used. There are 2 cross marks on the top glass mold and 2 cross marks on the bottom metal mod. The mold combination will wear the mold and the mold will have many blur and scratch. If using edge detects to recognize the mask, it will unstable and uncertain. Therefore, a geometric matching method was developed in this paper. It recognizes the mask by four corners around the mask. When the matching ratio was over 90%, the alignment accuracy was better than 0.5 μm.

9217-45, Session 7

3D meshes compression performance benchmarking

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In this paper we discuss the benchmarking of 3D mesh encoders compression performance. The tested encoders are the MPEG-SC3DMC codec (Scalable Complexity 3D Mesh Compression) based on the TFAN codec (Open3DGC implementation) and also we discuss the benchmarking of OpenCTM (Open Compressed Triangle Mesh) implementation. The geometry is compressed to a fraction of comparable file formats (3DS, STL, VRML, COLLADA...), and the format is easily accessible through a simple, portable API. The OpenCTM is a file format for storing 3D triangle meshes and is not for handling scenes, which make it versatile and widely used from online e-shopping system to game engines, and medical application to phone widgets. In comparison the 3D scene formats tend to be application specific.

9217-46, Session 7

Thermographic image analysis as a pre-screening tool for the detection of canine bone cancer

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Canine bone cancer is a common type of cancer that grows fast and may be fatal. It usually appears in the limbs which is called “appendicular bone cancer.” Diagnostic imaging methods such as X-rays, computed tomography (CT scan), and magnetic resonance imaging (MRI) are more common methods in bone cancer detection than invasive physical examination such as biopsy. These imaging methods have some disadvantages; including high expense, high dose of radiation, and keeping the patient (canine) motionless during the imaging procedures. This project study identifies the possibility of using thermographic images as a pre-screening tool for diagnosis of bone cancer in dogs. Experiments were performed with thermographic images from 40 dogs exhibiting the disease bone cancer. Experiments were performed with color normalization using temperature data provided by the Long Island Veterinary Specialists. The images were first divided into four groups according to body parts (Elbow/Knee, Full Limb, Shoulder/Hip and Wrist). Each of the groups was then further divided into three sub-groups according to views (Anterior, Lateral and Posterior). Texture features, spectral feature and histogram features were used for pattern classification. The best classification success rate in canine bone cancer detection is 90% with sensitivity of 100% and specificity of 80% produced by anterior view of full-limb region with nearest neighbor classification method and normRGB-lum color normalization method. Our results show that it is possible to use thermographic imaging as a pre-screening tool for detection of canine bone cancer.

9217-47, Session 7

Estimation and measurement of space variant features of imaging systems and analysis of their influence on accuracy in astronomical imaging

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Additional monitoring equipment is commonly used in astronomical imaging. This electro-optical system usually complements the main telescope during acquisition of astronomical phenomena or supports its operation e.g. evaluating the weather conditions. Typically it is a wide-field imaging system, which consists of a digital camera equipped with fish-eye lens. The wide-field imaging system cannot be considered as a space invariant because of space variant nature of its input lens. In our previous research efforts we have focused on measurement and analysis of images obtained from the subsidiary all-sky monitor WILLIAM (WIde-field aLL-sky Images Analyzing Monitoring system). Space variant part of this imaging system consists of input lens with 180° angle of view in horizontal and 154° in vertical direction. For a precise astronomical measurement over the entire field of view, it is very important to know how the optical aberrations affect characteristics of the imaging system, especially its PSF (Point Spread Function). Two methods were used for characterization of the space variant PSF, i.e. measurement in the optical laboratory and estimation using acquired images and Zernike polynomials. Analysis of results obtained using these two methods is presented in the paper. Accuracy of astronomical measurements is also discussed while considering the space variant PSF of the system.

9217-48, Session 7

Polar format statistical image processing based fiber optic pressure sensors

Muhammed Burak Alver, Kemal Fidanboylu, Onur Toker, Fatih Univ. (Turkey)

This paper presents detailed study on the development of a fiber optic sensor system to design a pressure sensor with different sensor configurations. The sensor used in the experiments is based on modal power distribution (MPD) technique. MPD technique is spatial modulation of the modal power in multimode fibers. Stress measurements and CCD camera based techniques were investigated in this research. Differently from earlier MPD works, all of the data gathered from CCD camera are used instead of using some part of the data, the ring shaped pictures taken from the CCD camera converted to polar coordinates, and so stripe shaped pictures are obtained. Four different features are calculated from these converted pictures. R component of the center of mass in the polar form is the first feature. It is calculated because it was expected to decrease monotonically with respect to increasing applied pressure. Second and third features are ring thickness in polar form with taking brightness of each pixel into account and ring thickness in polar form without taking brightness of each pixel into account. These features are calculated to analyze the effect of each pixel's brightness. It was expected for these two features that there will not be a big margin between them. Fourth feature is the ratio between third feature and first feature. A MATLAB code is written to correlate these features and applied force to the sensor. Various experiments conducted to analyze this correlation. Pictures are taken from CCD camera with 1 kg steps and from the written MATLAB code, graphics of each feature versus the applied force are generated. Experimental results showed that, the sensitivity of the proposed sensor is much higher than sensors that uses only some part of the collected data in earlier MPD studies. Furthermore, results are almost exactly the same that what was expected for the four proposed features. Results also showed that converting pictures to the polar form increases the sensitivity and reliability.

9217-49, Session 7

Vehicle detection and tracking in roadway traffic analysis using Kalman filter and features

Ahad Karimi Moridani, Seyyede Hoora Fakhrmoosavy, Pante'a Alipour, Islamic Azad Univ. (Iran, Islamic Republic of)

this paper presents a powerful algorithm of computer vision methods to traffic flow monitoring, vehicle detection and traffic analysis, which intend to develop the vehicle count system using an image processing technique in CCTV video outputs. This software-based vehicle counter can detect all vehicles through images instead of using expensive electronic sensors or cameras embedded in the side walks. This system processes captured video, detects vehicles in each frame, classifies the vehicles into four types and counts all of them, all by image/video processing techniques.

9217-50, Session 7

Quick-shift framework for color image segmentation based on invariant representation

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Quick-shift method is a common method for image segmentation. The quick-shift is sensitive to the choice of parameters, thus a quick tuning by hand is not sufficient. This paper proposes an automatic quick-shift framework for color image segmentation based on illumination invariant representation. We eliminate the factors that may affect image acquisition such as shadow and highlight by applying an invariant method for the input image. To reduce the number of colors of the invariant image for manual segmentation, we use a quantization process. The quick-shift method is then applied to extract superpixels from the invariant image to be compared with the manual segmented image. The initial parameters values are set, then the similarity between segmented image and quantized invariant image is calculated. The accuracy of the segmentation results is numerically demonstrated by the similarity measure. The algorithm is repeated several times automatically with changing the parameters values till reaching the highest similarity.

In experiments, we use a digital still camera for objects observation. The normalized color values were calculated for RGB channels by eliminating illumination effect. We examined the performance of the proposed method for a variety of color images including different objects of metals and dielectrics in experiments. The segmentation of the proposed method has much less noise. It is clear and has sharp edges compared to the invariant representation. The proposed method is better as its segmented images are clearer than the k-means segmentation method. The results show the performance and stability of the proposed framework.

9217-64, Session 7

A visible light imaging device for cardiac rate detection with reduced effect of body movement

Xiaotian Jiang, Ming Liu, Yuejin Zhao, Beijing Institute of Technology (China)

A visible light imaging device to detect human cardiac rate is proposed in this paper. A camera and several LEDs, acting as lighting source, are mounted in a small box to avoid the ambient light. The box is fixed to the forehead or palm to capture the video of this region, from which the cardiac rate can be acquired based on photoplethysmography (PPG) theory. And cross-positioning method and template matching method are used during the capture of video. The video signal is discomposed into three signal channels (RGB) and the region of interest is chosen to take the average gray value. The green channel signal can provide an excellent waveform of pulse wave on the account of green lights' absorptive characteristics of blood. And the result of red channel signal divided by green can help to obtain the cardiac rate more accurately. Independent component analysis (ICA), wavelet denoising algorithm and adaptive filtering are also used to optimize the waveform. Through the fast Fourier transform, the cardiac rate is exactly achieved. With this method, the effects of body movement are reduced to a large extent, therefore the cardiac rate can be detected even while people are in the

moving state and the waveform is largely optimized. Several experiments are conducted on volunteers, and the results are compared with the signals captured by a conventional PPG signal measurer from a finger. The results between these two modalities are exactly agreeable. This method to detect the cardiac rate largely reduces the effects of body movement and can probably be widely used in the future.

9217-51, Session 8

On iris detection for mobile device applications

Magdi A. Mohamed, Michel Sarkis, Ning Bi, Xin Zhong, Yingyong Qi, Qualcomm Inc. (United States)

No Abstract Available

9217-52, Session 8

Learning to predict where human gaze is using quaternion DCT based regional saliency detection

Ting Li, Yi Xu, Chongyang Zhang, Shanghai Jiao Tong Univ. (China)

Recently, some spectral domain saliency models have been proposed to meet real-time requirement of human gaze tracking tasks. However, current saliency detection methods used global PQFT and QDCT to locate jump edges of the input, which can hardly detect the object boundaries accurately. To address the problem, we improved QDCT-based saliency detection model by introducing superpixel-wised regional saliency detection mechanism. The local smoothness of saliency value distribution is emphasized to distinguish noises of background from salient regions. Our algorithm called saliency confidence can distinguish the patches belonging to the salient object and those of the background. It decides whether the image patches belong to the same region. When an image patch belongs to a region consisting of other salient patches, this patch should be salient as well. Therefore, we use saliency confidence map to get background weight and foreground weight to do the optimization on saliency map obtained by QDCT. The optimization is accomplished by least square method. The optimization approach we proposed unifies local and global saliency by combination of QDCT and measuring the similarity between each image superpixel. We evaluate our model on four commonly-used datasets (Toronto, MIT, OSIE and ASD) using standard precision-recall curves (PR curves), the mean absolute error (MAE) and area under curve (AUC) measures. In comparison with most state-of-art models, our approach can achieve higher consistency with human perception without training. It can get accurate human gaze even in cluttered background. Furthermore, it achieves better compromise between speed and accuracy.

9217-53, Session 8

Visualization of photo album on mobile devices

Changhwan Chun, Hyundai Motor Co. (Korea, Republic of)

No Abstract Available

9217-54, Session 8

Face recognition using the most representative sift images

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In this paper, face recognition using the most representative SIFT images is presented. It is based on obtaining the SIFT (SCALE INVARIANT FEATURE TRANSFORM) features in different regions of each training image. Those regions were obtained using the K-means clustering algorithm applied on the key-points obtained from the SIFT algorithm. Based on these features, an algorithm which will get the most representative images of each face is presented. In the test phase, an unknown face image is recognized according to those representative images. In order to show its effectiveness this algorithm is compared to other SIFT algorithms and to the LDP algorithm for different databases.

9217-57, Session 9

Multiple objects tracking with HOGs matching in circular windows

Daniel Miramontes-Jaramillo, Vitaly Kober, Ctr. de Investigación Científica y de Educación Superior de Ensenada B.C. (Mexico); Víctor H. Diaz-Ramirez, Ctr. de Investigación y Desarrollo de Tecnología Digital (Mexico)

In recent years tracking applications become important with development of new technologies like smart TVs, Kinect that tracks hand gestures and human limbs, augmented reality devices like Google Glass and Oculus Rift that track objects in real life and virtual environments. So, the tracking task in a video sequence provides different interesting problems to be solved. When a matching algorithm is used, a good prediction algorithm in each frame of a video sequence is required to reduce the search area for each object to be tracked as well as processing time. In this work we analyze the performance of different prediction techniques with a fast matching for a real-time tracking multiple objects. The used matching algorithm is based on histograms of oriented gradients. It carries out matching in circular windows, and possesses rotation invariance and tolerance to viewpoint and scale changes. Tested systems are implemented in a personal computer with GPU and compared in terms of errors of recognition and localization, and processing time in real scenarios. Such implementation takes advantage of current technologies and helps to process video sequences in real time for tracking several objects at the same time.

9217-59, Session 9

Markov random fields for static foreground classification in surveillance systems

Jack Fitzsimons, Trinity College (Ireland); Thomas T. Lu, Jet Propulsion Lab. (United States)

This paper presents a real-time system for the classification of static foreground between abandoned and removed objects in automated surveillance systems. Inspired by techniques used in exemplar based image completion and driven by the demands of our in-house developed surveillance system, our algorithm synthesizes the regions of interest (ROI) from frames before and after the event. This is done using patches from their source regions (i.e. the area of the image that is not under inspection). Patches are chosen based on their consistency and locality to the ROIs. An energy metric is then computed from the success of this region painting exercise and compared in order to determine which of the ROIs is most likely to have contained the object. While this concept synthesizing the ROI is novel, it holds many properties of some image completion methods, both working from similar Markov Random Field models, allowing us to leverage previous optimization techniques. After testing our algorithm on static foreground datasets found in CAVIAR, PETS 2006 and VISOR, we have shown that our algorithm is capable of matching the results of the state of the art detectors and improves on previous in painting based techniques in the presence of global illumination changes and large scaled patterns.

9217-60, Session 9

Single image dehazing using local adaptive signal processing

Jesus A. Valderrama, Victor H. Diaz-Ramirez, Ctr. de Investigación y Desarrollo de Tecnología Digital (Mexico); Vitaly Kober, Ctr. de Investigación Científica y de Educación Superior de Ensenada B.C. (Mexico)

Many outdoor images are degraded by light scattering which is introduced by the presence of suspended particles in the atmosphere due to haze. In such degraded images, the objects that are far from the camera suffer from a severe contrast loss and color richness. In this work, we present a local adaptive algorithm for single image dehazing. The proposed algorithm is able to estimate a dehazed image from an observed hazed scene by solving an objective function whose parameters are adapted to local statatistics of the hazed image inside a moving window. The proposed objective function is based on a trade-off among a local contrast enhancement of the dehazed signal and the mean-squared-error between hazed and dehazed signals. In order to achieve a high-rate signal processing, the proposed algorithm is implemented in a graphics processing unit (GPU) exploiting massive parallelism.

Experimental results obtained with a laboratory prototype are presented, discussed, and compared with those results obtained with existing single image dehazing methods in terms of objective metrics and computational complexity.

9217-61, Session 10

Adaptive live IP multicast of SVC with unequal FEC

Amir Lasri, Ben Guirion Univeristy (Israel); Avi Lev, Maoz Loants, Ofer Hadar, Ben-Gurion Univ. of the Negev (Israel)

Scalable Video Coding (SVC) is the name given to an extension of Annex G, the H.264/MPEG-4 AVC video compression standard. The objective of the SVC standardization was to enable the encoding of a high-quality video bitstream that contains one or more bitstream subsets. Each bitstream subset can be decoded and then combined with the other bitstream subsets to reconstruct the video with a quality similar to that achieved using the existing H.264/MPEG-4 AVG standard. A bitstream subset can represent a lower spatial or temporal resolution or a lower quality video signal (each separately or in combination) compared to the bitstream it is derived from. Different users have a variety of screen resolutions, quality requirements, computational power and bandwidth. This calls for a design that takes advantage of the qualities of SVC where each user receives a different subset of the bitstream according to the quality need. Using IP multicast, the different layers are extracted and sent over different multicast groups, to help optimize the network load. To overcome network variations, each user can adaptively decide how many layers he can receive according to the current network bandwidth conditions. In order to further enhance the performance of the system, another layer of error codes is added. The data in each layer of the bitstream is protected using PRO-MPEG FEC and the amount of overhead added is sensitive to network load and changes adaptively, while each layer receives an unequal amount of protection bits. Then the layers are aggregated into one completed reconstructed video stream. This results in an optimized use of the network bandwidth and better visual quality at the receiver side.

9217-62, Session 10

Real-time SHVC software decoding with multi-threaded parallel processing

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This paper proposes a parallel decoding framework for scalable extensions of HEVC (SHVC). Various optimization technologies are implemented on the basis of SHVC reference software SHM-2.0 to achieve real-time decoding speed for two layer spatial scalability configuration. The decoding process at each layer and the upsampling process are implemented in parallel and scheduled by a high level application task manager. Within each layer, multi-threading is applied to accelerate the layer decoding speed. The entropy decoding, reconstruction, and in-loop processing modules are pipeline designed with multiple threads based on groups of coding tree units (CTU). A group of CTUs is treated as a processing unit in each pipeline stage and is used to achieve better trade-off between degree of parallelism and synchronization. The motion compensation, inverse quantization, and inverse transform modules are further optimized with SSE4 SIMD instructions. Simulations on a desktop with Intel i7 processor 2600 running at 3.4 GHz show that the parallel SHVC software decoder is able to decode 1080p with spatial ratio of 2x at up to 60 fps (frame per second) and 1080p with spatial ratio of 1.5x at up to 50 fps for bitstreams generated with SHVC reference software encoder under SHVC common test conditions. The decoding speed and decoding resource usage are further compared at various bitrates with different optimization technologies and different number of threads.

9217-63, Session 10

Entropy-based optimal ROI determination for multichannel blind deconvolution

Mohd Z. Abdullah, Ahmad H. Shapri, Univ. Sains Malaysia (Malaysia)

Blind deconvolution is one of the most powerful techniques in image restoration especially in applications when the point spread function is unknown. This type of image restoration problem is inherently ill-posed due to the ill-conditioned properties of the convolution operators. It is well-known fact that the conditioning of this deconvolution procedure is greatly improved if multiple images of the same scene are acquired. However, the efficiency or vulnerability of this technique depends critically on the selection of the region of interest (ROI). Selecting an optimal ROI is still unresolved issue in this area of research. In this paper, a novel technique based on entropy is investigated for locating an optimal ROI. Using this technique the randomness of gray-level distribution generated by all pixels in the image is quantitatively measured. Also, a minimum average value of entropy in adjacent frames is also considered in the computation. The methods and procedures are tested using the Levin's database comprising of 32 blurred images with 255 x 255 pixel size each. The performance of the proposed algorithm is quantitatively assessed in terms of the peak signal-to-noise ratio (PSNR), the improvement signal-to-noise ratio (ISNR), and the universal image quality index (UIQI). The results indicate that the choice of ROI affects the restoration quality, yielding the best PSNR, ISNR and UIQI of 24.31 dB, 5.32 dB and 0.77 respectively. The proposed algorithm also outperformed the established single-channel blind deconvolution algorithm, resulting in the increased of PSNR, ISNR and UIQI by as much as 12.84 %, 52.79 % and 39.27 % respectively.

9217-65, Session 10

Information embedding to a real object by projecting a checkered-pattern carrier-screen image

Rui Shogenji, Shizuoka Univ. (Japan)

We propose an information embedding technique to a real object by projecting a checkered-pattern carrier-screen image as an illumination. The carrier-screen image is an information hiding technique, which can

decode a secret image physically by superimposing a periodic pattern. These carrier-screen images are now used for document security purposes such as anti-counterfeiting technology for the banknotes and also used for the entertainment application such as picture books, because of the feature of its visual decoding. As a kind of carrier-screen images, we have developed the checkered-pattern carrier-screen images, which can be physically decoded by superimposing a checkered pattern. The secret information is also visualized by image sampling with certain interval. As an example of decoding by image sampling, we proposed a decoding method with an ordinary compact digital camera. The encoded carrier-screen image has an almost uniform pattern, because modulating a checkered pattern generates it. It also has a good compatibility with digital images, because it is represented on a square pixel structure. Therefore, it is easy to display on a liquid-crystal display. Experimental results of decoding with a compact digital camera show effectiveness of the proposed system. Since the embedded information can be decoded by using an ordinary digital camera, our system expected to use not only steganographic purpose also prevention techniques on taking photos.

9217-66, Session 10

Adaptive image coding based on cubic-spline interpolation

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It has been investigated that at low bit rates, downsampling prior to coding and upsampling after decoding can achieve better compression efficiency than standard coding algorithms, e.g., JPEG and H. 264/AVC. However, at high bit rates, the sampling-based schemes generate more distortion. Additionally, the maximum bit rate for the sampling-based scheme to outperform the standard algorithm is image-dependent. To solve this problem, a practical adaptive image coding algorithm based on the cubic-spline interpolation (CSI) is proposed in this paper. This novel algorithm adaptively chooses the image coding method between the CSI-based scheme and the standard JPEG under a given target bit rate utilizing the so called rho-domain analysis. The experimental results indicate that compared with the standard JPEG, the proposed algorithm can show better performance at low bit rates and maintain the same performance at high bit rates.

9218-1, Session 1

Assessment of the clouds and the Earth's radiant energy system (CERES) flight model 5 (FM5) instrument's performance and stability

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The Clouds and the Earth's Radiant Energy System (CERES) scanning radiometer is designed to measure the solar radiation reflected by the Earth and thermal radiation emitted by the Earth. Four CERES instruments are supporting the EOS missions; two aboard the Terra spacecraft, launched in 1999 and two aboard the Aqua spacecraft, launched in 2002. A fifth instrument, Flight Model 5 (FM5), launched in October 2011 aboard the NPP satellite, began taking radiance measurements on January 27th, 2012. The CERES FM5 instrument uses three scanning thermistor bolometers to make broadband radiance measurements in the shortwave (0.3 – 5.0 micrometers), total (0.3 - >100 micrometers) and water vapor window (8 – 12 micrometer) regions. An internal calibration module (ICM) used for in-flight calibration is built into the CERES instrument package consisting of an anodized aluminum blackbody source for calibrating the total and window sensors, and a shortwave internal calibration source (SWICS) for the shortwave sensor. The ICM sources, along with a solar diffusor called the Mirror Attenuator Mosaic (MAM), are used to define shifts or drifts in the sensor response over the life of the mission. In addition, validation studies are conducted to assess the pointing accuracy of the instrument and understand any spectral changes that may occur with the sensors allowing for corrections to be made to the radiance calculations in later CERES data products. This paper summarizes the on-orbit behavior of the CERES FM5 instrument by outlining trends in the internal calibration data and discussing the various validation studies used to assess the performance and stability of the instrument.

9218-2, Session 1

Determination of the SNPP VIIRS SDSM screen transmittance from both yaw and non-yaw maneuver data

Ning Lei, Xuexia Chen, Sigma Space Corp. (United States); Xiaoxiong J. Xiong, NASA Goddard Space Flight Ctr. (United States)

The Visible/Infrared Imager/Radiometer Suite (VIIRS) aboard the Suomi National Polar-orbiting Partnership (SNPP) satellite carries out radiometric calibration of its reflective solar bands (RSB) primarily through observing an onboard solar diffuser (SD). The SD optical scattering property is measured by a bidirectional reflectance distribution function (BRDF). Once on orbit, the BRDF degrades over time and the degradation factor is determined by an onboard solar diffuser stability monitor (SDSM) which observes the Sun and the SD at almost the same time. When the SDSM observes the Sun, the solar energy enters the SDSM through a pinhole screen. The transmittance of the screen over a range of solar angles was determined prelaunch and tabulated. With the prelaunch determined SDSM screen transmittance, it is found that the SD BRDF degradation factor has many unrealistically large undulations over time (corresponding to different solar angles). Satellite yaw maneuvers were carried out around 110 days after launch, aiming to refine both the SD and the SDSM screen transmittances. The yaw maneuver orbits however, yield a large angular step size in the horizontal solar angle and as a result the yaw maneuver data is not able to resolve the SDSM screen transmittance accurately at a fine angular scale. In this Proceeding, we report a methodology to use both yaw maneuver and non-yaw maneuver data to determine the SDSM screen transmittance at a fine angular scale and show that using the newly determined SDSM screen transmittance, the SD BRDF degradation factor behaves much smoothly over time.

9218-3, Session 1

S-NPP VIIRS lunar observations

Jon Fulbright, Zhipeng Wang, Sigma Space Corp. (United States); Xiaoxiong J. Xiong, NASA Goddard Space Flight Ctr. (United States)

Lunar observations by the Suomi-NPP instrument VIIRS help our understanding of the radiometric calibration of the reflected solar bands (RSB). The spacecraft performs a scheduled roll maneuver approximately nine times per year to acquire lunar data at nearly constant phase angles. The instrument also captures lunar radiometric data at other times when the instrument Space View port serendipitously points at the Moon. In this paper, we present results from both the scheduled and unscheduled Moon observations, comparing the observed lunar irradiance to ROLO model results to provide calibration coefficients for each band, mirror side, and detector. These results can be evaluated directly to the primary RSB calibration method derived from the Solar Diffuser. This paper also discusses recent improvements to our methodology for measuring the lunar irradiance, including a new method for determining the lunar position within the field of view, an all-detector calibration methodology, and an assessment of the uncertainties in our lunar observations. This paper includes lunar observation data through June 2014.

9218-4, Session 1

Progress in the on-orbit calibration of SNPP VIIRS for ocean data processing

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The NASA VIIRS Ocean Science Team (VOST) has continued development of two independent calibrations of the SNPP VIIRS moderate resolution reflective solar bands using solar diffuser and lunar observations through June 2014. The supposition that the periodic residuals in the VIIRS lunar data from the USGS ROLO photometric model of the MOON arise from a wavelength-dependent libration effect for the sub-spacecraft point has been confirmed with an additional year of lunar observations. The VOST has also evaluated the effect of modulated relative spectral responses (RSRs) on the VIIRS calibration. The only major impact is on the band M1 (412 nm) lunar data. The effect on lunar observations for the other bands and on the solar observations for all bands is minimal. Fits to the solar calibration time series show mean residuals per band of 0.079-0.14%. Fits to the lunar calibration time series that account for the residual libration effects show mean residuals per band of 0.059-0.13%. Comparison of the solar and lunar time series shows that the relative differences in the two calibrations are 0.14-0.30%. Relative uncertanties in the VIIRS solar and lunar time series are comparable to those achieved for SeaWiFS, Aqua MODIS, and Terra MODIS.

9218-5, Session 1

On-orbit calibration methodologies for S-NPP VIIRS day night bands

Xiaoxiong J. Xiong, NASA Goddard Space Flight Ctr. (United States); ShihYan Lee, Zhipeng Wang, Aisheng Wu, Xuexia Chen, Ning Lei, Jon Fulbright, Sigma Space Corp. (United States)

One of the major improvements the VIIRS instrument made over its heritage sensors, such as MODIS and AVHRR, is its capability of making nighttime observations in the reflective solar spectral region. This is accomplished by a day night band (DNB). The VIIRS DNB is a panchromatic band with relative spectra response (RSR) ranging from visible to near infrared and its observations are made in different gain stages and aggregation modes. This paper provides an overview and assessment of different methodologies developed and implemented by the NASA VIIRS Calibration Support Team (VCST) to calibrate and characterize the DNB on-orbit performance. In addition to SD and lunar observations, the ground reference targets are used to examine the DNB calibration stability and calibration consistency with other reflective solar bands. The calibration impact due to sensor modulated RSR on various calibration approaches and effort to be made for future improvements are also discussed in this paper.

9218-76, Session 1

Operational in-flight calibration of NPP VIIRS in the visible using Rayleigh scattering

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Accurate radiometric calibration of satellite optical sensors is essential to retrieving ocean-color variables quantitatively in terms of absolute values. The accuracy requirements for absolute calibration are demanding since the signal to extract, i.e., the water-leaving radiance, is relatively small compared with the measured signal, dominated by atmospheric scattering. Consequently, retrieving water-leaving radiance to within ±5% in the blue in clear waters, the objective of major satellite ocean-color missions, requires knowing the top-of-atmosphere radiance to a small fraction of one percent. To achieve such level of accuracy, ocean-color project offices generally rely on the concept of "system" vicarious calibration, in which retrieved and measured water-leaving radiance are forced into agreement. The instrument is not considered separately from the atmospheric correction scheme, but part of the same system because both are necessary to estimate water-leaving radiance. A drawback is that quality in-situ measurements of water-leaving radiance are relatively scarce. Using a well-maintained site like MOBY, stability in the vicarious gains may only be obtained after 2-3 years, which is not satisfactory (vicarious gains should be fixed as early as possible during the mission operational phase, i.e., within one year after launch).

An alternative approach, which has the advantage of being purely radiometric (i.e., not linked to any atmospheric correction scheme) and can be implemented operationally, is to use oceanic areas with stable optical properties, where situations of clear sky, low wind speed, and low aerosol content are frequent. In such situations, and under favorable Sun and view angles, the dominant contribution to the satellite signal in the visible is due to scattering by molecules (Rayleigh scattering), which can be computed accurately. Since the suitable pixels may be numerous, the required absolute calibration accuracy may be statistically reached much faster than using in-situ measurements. This approach has been successful for the POLDER mission.

The Rayleigh scattering approach is investigated for NPP VIIRS. First, suitable oceanic areas are selected by analyzing long-term time series of satellite-derived water-leaving radiance, chlorophyll concentration, aerosol optical properties, and occurrence of clear sky and low wind speed conditions. Second, a sensitivity study is performed to define criteria that minimize the non-molecular component of the measured signal and provide the theoretical error budget for the radiance computed in each of the VIIRS spectral bands in the visible. Third, a method is developed to compute operationally, using a state-of-the-art radiation transfer code, the expected satellite radiance, and the method is applied to actual VIIRS imagery. Finally, the resulting calibration coefficients are compared with the pre-flight and current ones, and conclusions are made about the method's ability to converge quickly and properly for scientific applications and to help understand instrument changes during mission lifetime. The long-term objective is to integrate, in an operational and systematic way, all the appropriate calibration techniques available and bring about beneficial information about radiometric performance, not only for VIIRS, but also future ocean-color sensors.

9218-6, Session 2

SNPP VIIRS day-night band on-orbit radiometric calibration

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The Day-Night Band (DNB) on Suomi-NPP VIIRS is a visible/near-Infrared panchromatic band capable of observing the earth during both daytime and nighttime. The VIIRS DNB is the first in its class to have on-orbit radiometric calibration using on-board calibrators. The calibration processes include (1) using the Solar Diffuser (SD) observation of the Sun to determine the gain of the DNB's low gain stage; (2) using the SD signals outside of direct Sun illumination to compute the gain ratios between DNB's low-to-mid and mid-to-high gain stages; and (3) using the nighttime calibrator observations to track the dark offset drift. In this proceeding, we describe the approaches used by the NASA VIIRS Calibration Support Team (VCST) DNB calibration, and the process to provide consistent mission calibration Look-Up-Tables (LUTs).

9218-7, Session 2

VIIRS Day-Night Band (DNB) calibration methods for improved uniformity

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The Suomi-NPP VIIRS Day-Night Band (DNB) offers quantitative measurements of visible and near-infrared light over a dynamic range from full daylight to the dimmest nighttime scenes. This range presents a challenge to radiometric calibration, but the instrument has exceeded all of its absolute radiometric requirements. Nevertheless, striping and banding are still visible, day or night, but especially in low-light scenes. The causes may be cross talk, stray light or hysteresis in the data used for calibration. These issues combine to reduce the utility of these unique observations for gaining new insight on the nocturnal environment. This paper presents methods for improving gain and offset uniformity for both day and night scenes while maintaining absolute radiometric accuracy. We evaluate removal of fixed-pattern non-uniformity in dark scenes on a per orbit basis using three different techniques: i) tracking the darkest 25th percentile calibration sector signal; ii) taking the mean of filtered dark Earth-view scenes to determine offset; iii) minimizing correlated error for dark scenes within an aggregation zone. For gain uniformity we discuss some problems with the current calibration methods, and demonstrate a technique to minimize the correlated error between detectors and aggregation zones using the moment matching technique for moonlit scenes. A similar technique can be used for daytime and twilight scenes. An alternative cross-calibration technique between gain stages uses indirect illumination of solar diffuser view. The use of the space view and blackbody view for cross-calibration is also discussed. Histogram equalization is discussed for minimizing striping and banding. In all cases, data with stray light is filtered out to prevent contamination of the destriping process.

9218-8, Session 2

Assessment of on-orbit crosstalk impact for SNPP VIIRS VisNIR bands

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Electronic and optical cross-talk is one of the major challenges facing space-based Earth observing sensors, the effects of which could pose serious risks to the successful retrieval of geophysical information. There was an extensive effort during the SNPP VIIRS design and testing phase to reduce the on-orbit crosstalk impact, which included reworking of the VisNIR focal plane to reduce electronic crosstalk and extensive characterization of the optical crosstalk. This paper describes an approach to assess the level of optical and electronic crosstalk on the measured radiance, and thereafter the retrieved geophysical products. During SNPP VIIRS pre-launch testing, a set of electronic and optical cross-talk influence coefficients was derived from measurements, which represent the amount of signal contamination received by each detector when other detectors on the same focal plane were illuminated. These coefficients were used to assess the potential crosstalk and its uncertainty on typical SNPP VIIRS land, atmosphere and ocean scenes. The simulation results show SNPP VIIRS crosstalk contamination is very small, up to 0.3 % for the stressing scenes. These results are encouraging and constitute further evidence that SNPP VIIRS produces high quality imagery. The simulation approach presented in this paper could also be used for early crosstalk impact assessments for future VIIRS instruments.

9218-9, Session 2

Trending of SNPP ephemeris and its implications on VIIRS geometric performance

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This paper describes the trending results of the ephemeris data in the two and half years of operations of the Suomi National Polar?orbiting Partnership (SNPP) spacecraft since its launch in October 2011. The ephemeris data includes time stamped positions and velocities, which are used to derive altitudes and speeds. The orbital mean altitude has been maintained at 838.8 km through drag make-up maneuvers for. The mean speed is 7524 m/s with orbital period of 101.5 minutes. The altitude above the Equator is 829.8 km to within +/- 1 km peak-to-valley. Within an orbit, the altitude varies from 828 km to 856 km and the speed varies from 7503 m/s to 7537 m/s. The local time of ascending node oscillates slowly from 13:25:24 GMT at launch to 13:23:02 in November 2012, then back to 13:27:55 as of 31 January 2014. The inclination angle drifts from 98.65 degrees at launch to 98.72 deg (0.07 degrees more away from the poles) in 2 years.

The Visible Infrared Imaging Radiometer Suite (VIIRS) instrument onboard the SNPP satellite has a swath width of 3055 km over the Equator, making observations once a day over the Equator both in the day side and night side without under-lap from one scan to the next or from one orbit to the next. For latitude above 55 (TBR) degrees in the northern hemisphere or below -55 (TBR) degrees in the southern hemisphere, VIIRS makes daily observations two or more times, up to 14 times over the poles.

9218-10, Session 2

The ground track oblique Cassini projection used for producing VIIRS mapped imagery

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The Suomi-NPP Visible Infrared Imager Radiometer Suite (VIIRS) radiance is mapped to make image products using the ground-track Mercator (GTM) algorithm developed at Raytheon. This algorithm defines a process for transforming gridded map (x/y) coordinates of the image into Earth coordinates (longitude/latitude). The y-axis reference is the satellite ground track, which is mapped with an even scale. Great circles placed orthogonally with respect to the ground track define the x-axis. In its current state the algorithm is only defined for the Map-to-Earth (MtE) transformation, but the Earth-to-Map (EtM) transformation has no mathematical algorithm, and instead must use a slow search algorithm for every point. Because of this, the GTM is not a true map projection. This paper remedies this by describing an EtM transformation algorithm using a Ground Track Oblique Cassini (GTOC) projection. This is in somewhat similar to the Space Oblique Mercator (SOM) Projection developed for Landsat. However, Landsat has a very narrow swath, and the GTOC projection better preserves scale across a wider swath, making it more suited for sensors such as VIIRS. Also, unlike the SOM, it keeps the ground-track centered, which is a more efficient use of screen area when it is viewed. This paper describes details of the algorithm, including adjustments necessary for an elliptical orbit and an ellipsoidal Earth. It evaluates Map parameters including conformality and scale preservation, comparing this with other projections, including the SOM. It also evaluates improvements in efficiency relative to a search algorithm.

9218-11, Session 3

Comparison of AIRS, IASI, and CrIS radiances and trends at Dome C

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This paper describes the comparison of radiances and radiance trends at Dome C in Antarctica measured by three sensors—the Infrared Atmospheric Sounding Interferometer (IASI), the Cross-track Infrared Sounder (CrIS), and the Atmospheric Infrared Sounder (AIRS). AIRS and IASI have been in simultaneous routine operations since May 2007. All three instruments have been producing operational data simultaneously since April 2012. Dome C is on a high plateau and provides a source of nearly uniform dry scenes with a temperature range from about 190 K to about 250 K. Located on this plateau is an operational automated weather station that provides ground truth, including temperature measurements two meters above the surface every ten minutes. Calibration of infrared radiometers at cold scene temperatures is very difficult. But high accuracy even at cold temperatures is critical for establishing a climate-quality data record. Since CrIS is presently planned to serve as a follow-on to AIRS, it is important to understand any differences in their observed radiances. We will compare AIRS, IASI, and CrIS brightness temperatures in several window channels including those at wavenumbers 900 and 1232 cm-1.

9218-12, Session 3

AIRS Level-1C and applications to cross-calibration with MODIS and CrIS

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We introduce and illustrate applications of the AIRS Level-1C (L1C) data product. While each spectrum in the Level-1B (L1B) calibrated radiances is represented by 2378 channels, each spectrum in the L1C product is represented by 2645 channels, with monotonically increasing frequency. Typically 2000 of the 2378 L1B channels are copied unchanged into the 2645 channel array used in L1C. The dead or noisy channels in the L1B and new channels in the spectral gaps of L1B are filled using a Principal Component technique. We illustrate two applications of AIRS L1C: 1) to integrate over the band of broadband instruments such as MODIS and 2) resampling to emulate other hyperspectral instruments such as CrIS. The L1C data product will greatly facilitate the use of AIRS data for cross-calibration with other instruments.

9218-13, Session 3

Evaluation of the AIRS and CrIS relative radiometric calibration under cloudy conditions

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The validation of the radiometric calibration of virtually all infrared radiometers has previously been carried out under carefully selected, generally spatially uniform conditions, with the assumption that the radiometric accuracy of the data may be dependent on scene brightness temperature, but is independent of other scene unique conditions, such as scene spatial uniformity. The availability of AIRS and CrIS observations from polar orbits with the identical ascending node presents an opportunity to evaluate the validity of this assumption. For each day between May 2012 and May 2014 we collected 22,000 Random Nadir Spectra (RNS). We then analyzed the time series of the daily differences between AIRS and CrIS Probability Density Function (PDF) in the 900 cm-1 atmospheric window channel. Under polar conditions the differences between AIRS and CrIS are typically less than 50 mK for the 10%tile, the mean and the 90%tiles values of the PDF. Under area representative global conditions day and night CrIS is about 0.2K colder than AIRS at the 10%tile and mean values. These differences are well within the limits of the instrument requirements specification. However, the difference between AIRS and CrIS have a complicated zonal distribution, particular for the tropical zone. For day tropical land the CrIS PDF is 0.3 K warmer in the mean, 1K warmer in the 10%tile value (cold tails of the PDF) than AIRS. The reasons for these differences are still under investigation. The smallest differences between AIRS and CrIS are seen in zones with the smallest scene inhomogeneity, i.e. essentially cloud-free data, while tropical day land, which has the largest difference between AIRS and CrIS, has the highest scene inhomogeneity. A number of modifications to the CrIS radiometric calibration algorithms have been proposed.

9218-14, Session 3

Relative spectral response corrected calibration inter-comparison of S-NPP VIIRS and Aqua MODIS thermal emissive bands

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The S-NPP Visible Infrared Imaging Radiometer Suite (VIIRS) instrument is built with strong heritage from EOS MODIS, and has very similar thermal emissive bands (TEB) calibration algorithm, using a similar on-board calibrating source – a V-groove blackbody.

The calibration of the two instruments can be assessed by comparing the brightness temperatures retrieved from VIIRS and Aqua MODIS simultaneous nadir observations (SNO) from their spectrally matched TEB. However, even though the VIIRS and MODIS bands are similar there are still relative spectral response (RSR) differences and thus some differences in the retrieved brightness temperatures are expected. The differences depend on both the type and the temperature of the observed scene, and contribute to the bias and the scatter of the comparison.

In this paper we use S-NPP Cross-track Infrared Sounder (CrIS) data taken simultaneously with the VIIRS data to derive a correction for the slightly different spectral coverage of VIIRS and MODIS TEB bands – the CrIS spectra are used to derive the VIIRS and MODIS TEB band-average spectral radiance, which is then converted to brightness temperature. The correction accounting for RSR differences can also be derived using MODTRAN models based on the MODIS scene-type and compared to the values based on actual CrIS spectra.

The RSR-correction is derived for scenes of different types and at various temperatures and the behavior of the corrected, uncorrected, and MODTRAN-corrected VIIRS – MODIS TEB comparison as a function of temperature and scene type is investigated.

9218-15, Session 3

Calibrating historical IR sensors using MODIS, GEO, and AVHRR infrared tropical mean calibration models

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Long-term, remote-sensing-based climate data records (CDRs) are highly dependent on having consistent, well-calibrated satellite instrument measurements of the Earth's radiant energy. Therefore, by making historical satellite calibrations consistent with those of today's imagers, the Earth-observing community can benefit from a CDR that spans a minimum of 30 years. Most operational meteorological satellites rely on an onboard blackbody and space looks to provide on-orbit IR calibration, but neither target is traceable to absolute standards. The IR channels can also be affected by ice on the detector window, angle dependency of the scan mirror emissivity, stray-light, and detector-to-detector striping. Being able to quantify and correct such degradations would mean IR data from any satellite imager could contribute to a CDR. Recent efforts have focused on utilizing well-calibrated modern hyper-spectral sensors to inter-calibrate concurrent operational IR imagers to a single reference. In order to consistently calibrate both historical and current IR imagers to the same reference, however, another strategy is needed. Large, well-characterized tropical-domain Earth targets have the potential of providing an Earth-view reference accuracy of within 1 K.

To that effort, NASA Langley is developing an 11-?m tropical mean calibration model in order to calibrate historical AVHRR instruments. Using Aqua-MODIS as a reference, models are built based on spatially/temporally binned MODIS, MODIS-equivalent GEO, and AVHRR brightness temperatures. Assessing similar climatology bins from MODIS and GEO, and then the same from GEO and AVHRR, will allow for the calibration of historical AVHRR sensors, and thereby establish a climate-quality IR data record.

9218-16, Session 4

Assessment of several Pseudo Invariant Calibration Sites (PICS) for the post launch calibration of optical sensors

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Over the last 15 years, several large uniform area sites, often called Pseudo Invariant Calibration Sites (PICS), have been used as a benchmark for monitoring the on-orbit radiometric calibration of optical sensors. The Committee on Earth Observation Satellite (CEOS) has endorsed a set of these sites that are considered optimal for temporal trending and the list can be found at http://calval.cr.usgs.gov/rst-resources/sites_catalog/. In this paper we attempt to rate the quality of these sites by assessing their temporal uncertainties using nadir observations from stable instruments. Results of work done to understand the probable sources of temporal uncertainties by analyzing the homogeneity of the site and meteorological properties of the site will be presented. Thus this work will provide useful metrics to identify key PICS that are the most suitable for monitoring the radiometric stability of space- based Earth observing instruments. In this study band specific temporal stability of the site is calculated by using average top of atmosphere (TOA) reflectance over the standard Region of Interest (ROI). Site specific empirical Bidirectional Reflectance Distribution Function (BRDF) models are used to account for the BRDF effect due to varying solar zenith angles. Two probable sources of uncertainties investigated are the presence of non-uniform pixels due to vegetation growth and uncertainties due to the intervening atmospheric conditions at the time of

overpass. Normalized Vegetation Difference Index (NDVI) is calculated to assess whether the target being observed contains vegetation. Similarly atmospheric variables such as Aerosol Optical Depth (AOD), wind speed and water vapor data available in National Oceanic and Atmospheric Administration (NOAA) databases are be useful to not only understand the meteorological properties of the sites but also to assess how these variables can impact the temporal stability of the target. The sensors used in this study include Landsat 7 Enhanced Thematic Mapper Plus (ETM+), Terra and Aqua MODIS. Not only have these sensors been extremely stable but they also acquire images over these PICS regularly. Results of from this work provide refined uncertainty measurements for popular PICS locations.

9218-17, Session 4

Assessment of VIIRS radiometric performance using vicarious calibration sites

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Radiometric performance of satellite instruments need to be regularly monitored to determine if there is any drift in the instrument response over time despite the calibration with the best effort. If the drift occurs, it needs to be characterized in order to keep the radiometric accuracy and stability well within the specification. Instrument gain change over time can be validated independently using many techniques such as using stable earth targets (desert, ocean, snow sites etc), inter-comparison with other well calibrated radiometers (using SNO, SNO-x), deep convective clouds (DCC), using lunar observations etc. This study focus on using vicarious calibration sites for the assessment of calibration stability of S-NPP VIIRS reflective solar bands (RSB). The calibration stability is primarily analyzed by developing the top-of-atmosphere (TOA) reflectance time series over these sites. In addition, the radiometric bias relative to AQUA MODIS analyzed over some of these calibration sites will also be presented. The radiometric bias will be quantified in terms of observed and spectral bias. The spectral characterization and bias analysis will be performed using hyperspectral measurements and radiative transfer models such as MODTRAN.

9218-18, Session 4

On-orbit validation methods using the Clouds and Earth's Radiant Energy System (CERES) solar calibration versus deep convective cloud ratios

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The Clouds and Earth's Radiant Energy System (CERES) scanning thermistor bolometers measure earth-reflected solar and earth-emitted long-wave radiances, at the top- of-the-atmosphere. The bolometers measure the earth radiances in the broadband shortwave solar (0.3-5.0 microns) and total (0.3->100 microns) spectral bands as well as in the 8->12 microns water vapor window spectral band over geographical footprints as small as 10 kilometers at nadir. December 1999, the second and third set of CERES bolometers was launched on the Earth Observing Mission Terra Spacecraft. May 2003, the fourth and fifth set of bolometers was launched on the Earth Observing Mission Aqua Spacecraft. Recently, (October 2011) the sixth instrument was launched on the National Polar-orbiting Operational Environmental Satellite System Preparatory Project (Suomi NPP) Spacecraft. The mirror attenuator mosaic (MAM), a solar diffuser plate, was built into the CERES instrument package calibration system in order to define on-orbit shifts or drifts in the sensor responses. The shortwave and shortwave part of the total-wave sensors are calibrated using the solar radiances reflected from the MAM's. Each MAM consists of baffle-solar diffuser plate systems, which guide incoming solar radiances into the instrument fields of view of the shortwave and total wave sensor units. The MAM diffuser reflecting type surface consists of an array of spherical aluminum mirror segments, which are separated by a Merck Black A absorbing surface, over-coated with SIOx (SIO2 for PFM). Thermistors are located within each MAM plate and the total channel baffle. The CERES MAM is designed to yield calibration precisions approaching .5 percent for the total and shortwave detectors. The Terra FM1 and FM2 shortwave channels and the FM1 and FM2 total channels MAM calibration systems showed shifts in their solar calibrations of 1.5, 2.5, 1.5 and 6 percent, respectively within the first year. The Aqua FM3, and FM4 shortwave channels and the FM3 and FM4 total channels MAM calibration systems showed shifts in their solar calibrations of 1.0, 1.2, 2.1 and .8 percent, respectively within the first year. Explanations have attributed the MAM reflectance changes to on-orbit solar ultraviolet/atomic oxygen/out-gassing induced chemical changes to the SIOx coated MAM assembly and to a lessor extent the shortwave filter and/or the total channel detector during ram and solar exposure. The Soumi NPP FM5 is still after one year displaying a stability of less than .5 percent. In this presentation, the use of a two channel ratio comparison technique is used to identify MAM related changes vs telescope sensor changes while staring at different reflected solar irradiance sources with the same channels will be presented along with on-orbit measurements for the twelve years the CERES instruments have been on-orbit.

9218-19, Session 4

Cross-calibration of Landsat 5 TM, and Landsat 8 OLI with Aqua MODIS using PICS

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The Thematic Mapper (TM) onboard the Landsat 5 (L5) has provided an unprecedented amount of earth observations for more than 25 years since its launch on March 1, 1984. The MODIS onboard the Aqua satellite is a part of the afternoon constellation of spacecraft and has been successfully providing near-continuous observations of the earth's surface and atmosphere. A synergistic use of TM and MODIS reflective solar bands (RSB) measurements is immensely beneficial to the broad user community. A consistent radiometric calibration between the sensors is a prerequisite for creating high quality science products. Various pseudo-invariant calibration sites (PICS) identified by the CEOS have been widely used to monitor the on-orbit calibration consistency for a number of sensors. Near-simultaneous observations of the Saharan PICS by L5 TM and Aqua MODIS are used in this study. The top-of-atmosphere (TOA) reflectance from the spectrally matching RSB are corrected for test site Bi-directional Reflectance Distribution Function (BRDF), relative spectral response (RSR) mismatch, and impacts for atmospheric water-vapor, and used to estimate the long-term calibration differences between the two sensors. The Operational Land Imager (OLI) onboard the Landsat 8 (L8) launched in February, 2013, is a follow-on mission to maintain the continuity of Landsat acquisitions. Similar cross-calibration methodology was extended to compare the spectrally matching bands of Aqua MODIS with OLI.

9218-58, Session PMon

Examination of the angular dependence of the SNPP VIIRS Solar Diffuser bidirectional reflectance distribution function degradation factor

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Modern Earth-orbiting Earth-observing remote sensing sensors often use onboard solar diffusers (SD) to calibrate their reflective solar bands (RSB), such as the Visible/Infrared Imager/Radiometer Suite (VIIRS) aboard the Suomi National Polar-orbiting Partnership (SNPP) satellite. The SD's optical scattering property is measured by a bidirectional reflectance distribution function (BRDF). Once on orbit, the BRDF is found to degrade over time and the degradation factor is determined by, in the case of SNPP VIIRS, an onboard solar diffuser stability monitor (SDSM) which observes the SD at a fixed view angle (relative to the SD surface). The SNPP VIIRS RSB however, observes the SD at a different angle. It is conventionally assumed (for cases like VIIRS) that the BRDF degradation factor is angle independent and hence the degradation factor determined by the SDSM is used to calibrate the RSB. We examine the angular dependency of the SNPP VIIRS SD BRDF degradation factor. We find that the degradation factor is clearly angle dependent over the shorter wavelengths of the RSB (< 700 nm), and the larger the degradation the stronger the dependency.

9218-59, Session PMon

Lidar monitoring of organic matter in the Pearl River estuary

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The Pearl River is a complex river network under the influence of heavy urbanization and industrialization. A dual-wavelength lidar fluorosensor system for fast diagnosis of chromophoric dissolved matter (CDOM) in water in the Pearl River estuary was discussed. The laser-induced fluorescence (LIF) system used two lasers as excitation sources with wavelength at 355nm and 532 nm, and a hyperspectral CCD spectrometer was used to record the fluorescence signal. The lidar fluorosensor was built on a porous aluminium alloy plate with orthogonal Czerny-Turner optical configuration. The excitation light direction was perpendicular to the detector, in order to eliminate the elastic scattering and two dichroic mirrors perpendicular to directions of excitation light and detectors were deployed to enhance the fluorescence intensity. During measurements, ambient and background noises is subtracted from raw spectra and water Raman scattering is used to correct laser fluorometer data for effects of water optical attenuation. The overlapping fluorescence spectra of water Raman scattering and CDOM were separated with fitting Gaussian of the least squares method. Using the instrument in the Pearl River estuary, high correlation was observed between CDOM absorption coefficient and laser fluorescence. In addition, fluorescence measured by in situ laser fluorometer compared very well to the values obtained using more sophisticated laboratory spectrophotofluorometer. The in situ results demonstrated rapid characterization of dissolved organic matter can be obtained by the LIF technique.

9218-60, Session PMon

Status of time-dependent response versus scan-angle (RVS) for Terra and Aqua MODIS reflective solar bands

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The MODIS has 20 Reflective solar bands (RSB), which are calibrated using a solar diffuser (SD) and the near-monthly scheduled lunar observations via the space view (SV) port. Observed at two different angles of incidence (AOI), the sensor responses from SD and Moon measurements are used to track the on-orbit RSB gain changes as well as the Response versus Scan-angle (RVS) changes. The MODIS RSB have been experiencing wavelength dependent degradation since launch with the largest degradation observed at the shorter wavelengths. In addition to SD and lunar observations, the MODIS Characterization Support Team (MCST) regularly monitors the response trending over selected desert sites at different AOI. After about 6 years on-orbit, the SD was determined to be inadequate in accurately characterizing the gain for several short-wavelength RSB (Terra bands 1-4, 8 and 9 and Aqua bands 8 and 9) resulting in a temporal drift. In Collection 6 (C6), a new algorithm using the Earth-view (EV) measurements from pseudo-invariant desert sites was developed to overcome this artifact which resulted in a significant improvement in the long-term calibration consistency of the MODIS Level 1B (L1B) products. This approach is formulated for all RSB, and its application was recently extended to Terra band 10, leading to a significant improvement in the ocean-color products. This paper discusses the current status and performance of the on-orbit RVS characterization as applied in C6. Also, the various challenges and future improvement strategies associated with trending the EV response for the high-gain ocean bands are discussed.

9218-61, Session PMon

Development of 2D deconvolution method to repair blurred MTSAT-1R visible imagery

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Spatial cross-talk has been discovered in the visible channel data of the Multi-functional Transport Satellite (MTSAT)-1R. The slight image blurring is attributed to an imperfection in the mirror surface caused either by flawed polishing or a dust contaminant. An image processing methodology is described that employs a two-dimensional deconvolution routine to recover the original undistorted MTSAT-1R data counts. The methodology assumes that the dispersed portion of the signal is small and distributed randomly around the optical axis, which allows the image blurring to be described by a point spread function (PSF) based on the Gaussian profile. The PSF is described by 4 parameters, which are solved using a maximum likelihood estimator using coincident collocated MTSAT-2 images as truth. A sub-pixel image matching technique is used to align the MTSAT-2 pixels into the MTSAT-1R projection and to correct for navigation errors and cloud displacement due to the time and viewing geometry differences between the two satellite observations. An optimal set of the PSF parameters is derived by an iterative routine based on the 4-dimensional Powell's conjugate direction method that minimizes the difference between PSF-corrected MTSAT-1R and collocated MTSAT-2 images. This iterative approach is computationally intensive and was optimized analytically as well as by coding in assembly language incorporating parallel processing. The PSF parameters were found to be consistent over the 5-days of available daytime coincident MTSAT-1R

and MTSAT-2 images, and can easily be applied to the MTSAT-1R imager pixel level counts to restore the original quality of the entire MTSAT-1R record.

9218-62, Session PMon

Correction method of physical temperature variation for airborne double-antenna microwave radiometer

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In this paper, the principle of the Ka-band airborne double-antenna microwave radiometer based on the auto-gain compensative and noise coupling techniques is reviewed firstly. The radiometer has been applied successfully to detect the atmospheric cloud liquid content. Although the auto-gain compensative technique can compensate the gain fluctuation to keep the radiometer's stability by measuring the output variation of reference noise source, it also introduces measurement error caused by the physical temperature change of the reference noise source. For this reason, a temperature correction method for the output voltage of this radiometer is proposed. The corrected equations are derived by using the regression relationship between the measurement error and the physical temperature of the reference noise source. In order to demonstrate the feasibility of this method, the outdoor contrast experiment was carried out. We covered every antenna aperture respectively with a piece of microwave blackbody material for the observing target. For the 30° antenna channel, the RMSE of the two-point calibration method is 2.039K while the RMSE of the correction method is 0.718K. For the 90° antenna channel, the RMSE of the two-point calibration method is 2.113K while the RMSE of the correction method is 0.448K. The results prove that the correction method can effectively correct the output of the radiometers with the auto-gain compensative technique.

9218-63, Session PMon

An adaptive GIMS-technology for the remote monitoring of aquatic ecosystems

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Aquatic ecosystems are one of the important objects of geoinfomation monitoring. Knowledge of microwave attenuation properties of water systems needed in this respect since attenuation values and their dependence on frequency and biometrical features afford a basis for microwave remote sensing retrieving algorithms.

One of perspective approach to the solution of the problems arising here is GIMS-technology(GIMS = GIS + model).The basic scheme of collection and processing of the information in geoinformation monitoring system(GIMS) recognizes that effective monitoring researched object is possible at complex use of methods of simulation modeling, collection and processing of the information.

One of the basic tasks of geoinformation monitoring of an environment is automation of data processing of measurements with the principal goal of the task decision for phenomena detection and classification on a water surface. The methods and algorithms of cluster and discriminant analysis for the classification and qualitative interpretation of remote sensing data characterizing the water and ice surface are considered.

The problem of classification of aquatories using the remote sensing measurements is one of important among them. Various algorithms of the theory of images recognition, statistical decisions and cluster analysis are used to solve this problem. The mathematical model describing the background characteristics of water surface spottiness is proposed. Operative software for this model is realized.

The results of the software application to the satellite data processing for the Atlantic, Pacific and Arctic regions are given.

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9218-64, Session PMon

Design of the precise uniform light source based on optically connected integrating spheres for VIIR calibration

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The paper presents the design procedure that makes possible identification of the optimal parameters of the proposed light sources. These precise uniform light sources have a form of several or multiple optically connected integrating spheres. It contains several primary integrating spheres of small diameters which are installed on a secondary integrating sphere of bigger diameter. The initial light sources – halogen lamps or light emitted diodes are installed inside the primary integrating spheres. These spheres are mounted on the secondary integrating sphere. The radiation comes from the primary integrating spheres to the secondary one through diaphragms which diameters can be varied. The secondary integrating sphere has an output aperture from where uniform radiance emits. Due to high photometric and metrological characteristics the proposed light sources can be considered as one of the best candidates for VIIR calibration in optical range 0.4 – 2.3 μm. The paper discusses the principal engineering aspects connected with design of these light sources such as optimal selection of integrating sphere geometry, halogen lamps, power supply, materials and etc.

9218-65, Session PMon

CLARREO calibration uncertainty assessment tool: status and path forward

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The Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission is designed to make SI-traceable measurements and provide a long-term benchmarking data record for the detection, projection, and attribution of changes in the Earth's climate system. The CLARREO mission will include instruments operating in the reflected solar (RS) wavelength region from 320 nm to 2300 nm and the thermal infrared wavelength region from 5 μm to 50 μm. A major objective of CLARREO is to improve the accuracy of SI-traceable absolute calibration in the infrared and reflected solar wavelengths.

In this paper we describe a tool developed to assess the uncertainty of the top of the atmosphere (TOA) Earth reflectance, to be measured by the CLARREO reflected solar (RS) instrument. The tool provides an error estimate based on the preliminary prototype instrument design. The on-orbit calibration approach currently implemented in the tool uses a direct view of the Sun through an attenuator. Several attenuation approaches are considered and incorporated as options of viewing the Sun through: a pinhole; a perforated plate; a combination between a pinhole and reduced exposure time and/or a neutral density (ND) filter. Additional approaches can readily be implemented. The tool is realized in Excel and is intended to facilitate error budget assessments specifically of the CLARREO RS instrument. Towards deriving a realistic estimate we started compiling a database of values for the various uncertainty contributors using results from testing prototypes or from other missions utilizing similar design.

9218-66, Session PMon

Post-launch performance evaluation of the OMPS Nadir Mapper and Nadir Profiler

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The Joint Polar Satellite System (JPSS) represents the latest generation of polar-orbiting satellites operated by the National Oceanic and Atmospheric Administration (NOAA). The first in the JPSS series of satellites, the Suomi National Polar-orbiting Partnership (NPP) spacecraft was launched in November 2011 to bridge the gap between the current Polar Operational Environmental Satellites (POES) and the future JPSS-1. The Ozone Mapping Profiler Suite (OMPS) is a suite of hyperspectral instruments onboard the Suomi NPP spacecraft designed to continue atmospheric ozone records through both atmospheric profiles and global distribution mapping. OMPS will also be included on the future JPSS payloads. In order to properly extend measurements from previous ozone instruments, including the Solar Backscatter Ultraviolet (SBUV) instrument on POES, proper OMPS calibration is necessary. In this study, the post-launch performance of the OMPS Nadir Mapper (NM) and Nadir Profiler (NP) are evaluated through their Sensor Data Records (SDRs), which validates their end-to-end calibration. This is achieved through stability monitoring and inter-comparison.

9218-67, Session PMon

Using the moon to evaluate the radiometric calibration performance of S-NPP VIIRS thermal emissive bands

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The S-NPP VIIRS thermal emissive bands (TEB) are radiometrically calibrated on-orbit with reference to an aboard blackbody (BB) operated at a nominal temperature of 292 K. The quality of the calibration can be evaluated at other temperatures using independent thermal sources. The thermal properties of the lunar surface are extremely stable over time, making it a feasible target for the TEB calibration stability assessment for the space-borne sensors with regular lunar observation capability. VIIRS is scheduled to view the Moon on a nearly monthly basis at approximately the same lunar phase angle. In this paper, the brightness temperatures (BT) of the lunar surface retrieved using the calibration coefficients derived from the BB calibration are trended for VIIRS TEB on a detector basis. The lunar surface temperature varies greatly with location and also oscillates seasonally with the solar illumination geometry, with many of the lunar regions saturating the TEB detectors. Therefore, the trending must base on the regions of the Moon that do not saturate the detectors at any lunar event and thus their BT can be consistently retrieved. To achieve that, a temporally dynamic spatial mask is built for each detector to clip the locations of the Moon that may saturate the detector at any lunar event. Selected pixels of the remaining lunar images are then trended. The results show the radiometric calibration of all TEB detectors has been stable since the launch of VIIRS.

9218-68, Session PMon

Comparing Hyperion Lunar Observation with Model Calculations in Support of GOES-R Advanced Baseline Imager (ABI) Calibration

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Radiometric stability of the lunar surface and its smooth reflectance spectrum makes the moon an attractive candidate for calibrating satellite-based hyper/multi-band visible and infrared imagers. Long-term performance monitoring of satellite instrument using Moon can reveal the degradation of instruments. In this paper, analysis of Hyperion lunar observations and comparison with lunar model are performed in support of Cal/Val activities for satellite photometric imager such as GOES-R Advanced Baseline Imager (ABI) instrument. Hyperion makes hyper-spectral observations of the moon regularly with moon phase mostly at 7 degree and it covers visible and shirt-wavelength infrared (SWIR) channels with 10 nm spectral resolution. Five Hyperion lunar observations are analyzed. Lunar reflectance is derived from Hyperion observation and the mean absolute lunar spectral reflectance difference between Hyperion derivation and lunar model is 4.0 ± 2.62%. Through reflectance comparison, over-compensation of two strong atmospheric water absorption bands in Hyperion calibration is identified. The radiometric variance and degradation of Hyperion are assessed. To support the calibration of GOES-R ABI, hyper-spectral data of Hyperion lunar observation is convoluted with ABI spectral response functions for reflective solar bands to synthesize predicted lunar images to be observed by ABI. Lunar irradiances are derived from these synthesized lunar images for ABI and compared with lunar model predictions to quantify spectral biases. Long-term lunar imaging window of opportunities for GOES-R ABI are also assessed. The ability of using lunar model and Hyperion observation to calibrate satellite visible and SWIR sensors and reduce the measurement uncertainties is essential to support post-launch Cal/Val activities of GOES-R ABI.

9218-69, Session PMon

UV-elastic lidar for observations of tropospheric aerosol in the tropical and Andean region of Colombia

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An ultraviolet elastic backscatter lidar is described. It is based on a Q-switched powerful frequency doubled Nd:YAG laser (output pulse power: up to 400 mJ at 1064 nm; up to 200 mJ at 532 nm; up to 80 mJ at 355 nm; pulse duration 6 ns FWHM; repetition rate 10 Hz). A Newtonian telescope (20 cm diameter, 120 cm focal length) collects backscattered radiation from atmospheric particles and molecules. Lidar's spectral receiving module consists of four channels. The first two channels separate and detect elastic-backscattered lidar signals at laser wavelengths 532 nm and 355 nm, respectively. In the other two channels resulting from Raman backscattering of laser third harmonic (355 nm), a radiation at a wavelength of 407 nm is selected and detected by atmospheric water vapor, and 387 nm by atmospheric nitrogen molecules. Experimental profiles of the aerosol backscattering coefficient demonstrating measurement abilities of the system are shown and discussed. Particularly, the profiles containing signals from biomass burning aerosol, hazy atmospheric areas and traces of marine aerosol (Caribbean and Pacific) over city of Medellin (6° 15´38.37´´, 75° 34´40.46´´, 1483 m a.s.l.), Colombia.

9218-70, Session PMon

Estimation of a coaxial tropospheric lidar overlap function from analytical calculations and real measurements

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The geometrical form factor or overlap function of Lidar systems describes the efficiency with which light is coupled into its detector as a function of height, which means the degree of coupling between a telescope field of view (FOV) and laser beam near the lidar system. Incomplete coupling limits the accuracy, for example, to determine the height boundary layer (BL), which leads to large systematic errors in short range aerosols backscattering profiles, where aerosol is both most abundant and most variable. Very techniques have been proposed to estimate the overlap function. We show the results of estimating for coaxial tropospheric lidar from analytical calculations validated by comparison with real measurements for height below 100 m.

9218-71, Session PMon

Technology demonstrator of radiation resistant photon counting detector

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The design, construction and performance test results of photon counting detector technology demonstrator based on silicon avalanche photodiodes is reported. This photon counting device have been designed and optimized for extremely high stability of their detection (optical to electrical) delay. Applications in the mind are fundamental metrology in space and optical time transfer in space. The single photon avalanche diode structure manufactured on silicon using the K14 technology is used as a sensor with 100 microns circular active area. The sensor is operated in an active quenching and gating mode. The photon detection efficiency exceeds 40 % in a wavelength range spanning from 500 to 800 nm. The single shot timing resolution is better than 20 ps rms. Its detection delay is stable within ± 600 fs over several days of operation, in a sense of time deviation the detection delay stability of 200 fs has been achieved. The exceptional radiation tolerance of the detection chip itself has been verified in a series of experiments. All used components in demonstrator have radiation resistant equivalents.

9218-72, Session PMon

On-orbit MTF estimation of high resolution satellite optical sensor using reflected point sources

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Modulation Transfer Function (MTF) is an important parameter for characterizing the spatial resolution and the image quality of satellite optical sensors. Though the MTF is strictly measured in laboratory prior to flight, the majority of the life of these optical sensors is spent on orbit, and it is during this time that the sensor is actually acquiring data for which it was designed. Therefore, it is necessary to estimate their spatial performances to determine if any subsystem degradations occur over their life cycle. With the advent of high spatial resolution satellite sensors, it is more important to assess the spatial characteristics of these imaging systems. The PSF is always a bidimensional spatial function and may not only be non-circular, but also vary with location in the focal plane. However, previous analyses of PSF/MTF for high resolution satellite sensors have been usually performed using only one-dimensional techniques. Hence, A new technique for two-dimensional on-orbit MTF analysis has been developed that uses reflected point source. It can directly obtain the Point Spread Function (PSF) of an imaging system and then MTF plots. According to the input/output relationship, the discrete Line Spread Function (LSF) can be acquired by way of solving non-linear equations from the experimental point images. Additionally, the Gaussian model which is usually used to characterize the PSF of high spatial resolution satellite optical imaging systems can be also verified and validated by curve fitting.

9218-73, Session PMon

A temperature calibration method for CDOM fluorescence LIF lidar

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The influence of temperature change on the determined concentrations of dissolved organic matter (DOM) in water was investigated by laser induced fluorescence (LIF) technique in laboratory. The effect of temperature on CDOM fluorescence was investigated in freshwaters of Xixi River and in aqueous standards. The total luminescence spectra (TLS) of CDOM in several types of water samples with laser-induced fluorescence (LIF) measurements using a 405 nm wavelength excitation source were measured in the laboratory, and the spectra of CDOM were pointed out and obtained with spectral fluorescence signature (SFS) technique. The spectrum of water Raman scattering and fluorescence of CDOM were separated from TLS with fitting Gaussian of the least squares method, and the curve of fluorescence peak intensity of CDOM against corresponding concentration of CDOM is showed. A temperature calibration equation was derived to standardize CDOM fluorescence measurements to a specific reference temperature. The form of the equation is: FCDOM=FM/[1+r(TM–TR)], where T is temperature (°C), r is the temperature-specific coefficient of fluorescence (°C–1), FM is the measured fluorescent intensity and the subscripts TR and TM stand for the reference and measured values. Laboratory experiments with a portable hyperspectral LIF LiDAR showed that CDOM fluorescence intensity decreased as ambient water temperature increased. High correlation (R2=0.91) was observed between concentration of CDOM and fluorescence normalized to water Raman scattering with the temperature calibration method. When applied to field data, temperature calibration removed the effect of multi-day trends in water temperature, and it also damped the diel CDOM cycle. We conclude that temperature calibration is a necessary and important aspect of CDOM monitoring using in situ fluorescence sensors.

9218-74, Session PMon

Developing an automated global validation site time series system for VIIRS

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The Visible and Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar-Orbiting Partnership (NPP) satellite has 22 spectral bands, with 14 Solar Reflective Bands (RSB), 7 Thermal Emissive Bands (TEB) and 1 Day-Nigh Band (DNB). Long-term time series of TOA reflectance, brightness temperatures, and band ratios over well-established validation sites provide important information for post-launch calibration stability monitoring. However, such data are usually obtained manually and are extremely labor intensive. Only limited sites can be monitored for a limited period of time in previous studies.

In this study, we present an automated and highly extensible global validation sites time series system for VIIRS. VIIRS sensor data records over validation sites are obtained from NOAA and NASA NPP product archives. The system can be configured to performance automatic update daily, weekly, or monthly. It currently supports 17 globally distributed sites, such as the Antarctica Dome C, MOBY, Libyan 4, and Qinghai Lake, majority of which are recommended by the CEOS Working Group on Calibration & Validation (WGCV). The radiometric stability of VIIRS band over these sites is discussed. New sites can be added into the system without any software code modification. We plan to extend this system to support VIIRS/MODIS Simultaneous Nadir Overpass time series. The system can also be adapted easily to other instruments that have similar sensor data record archive available.

9218-75, Session PMon

Statistical analysis of the electronic crosstalk correction in Terra MODIS Band 27

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The first MODerate-resolution Imaging Spectroradiometer (MODIS), also known as the Proto-Flight model (PFM), is on-board the Terra spacecraft and has completed 14 years of operation as of December 18, 2013. MODIS remotely senses the Earth in 36 spectral bands, with a wavelength range from 0.4 µm to 14.4 µm. The 36 bands can be subdivided into two groups based on their spectral responsivity as Reflective Solar Bands (RSBs) and Thermal Emissive Bands (TEBs). Band 27 centered at 6.77 µm is a TEB used to study the global water vapor distribution. It was found recently that this band has been severely affected by electronic crosstalk. The electronic crosstalk magnitude, its on-orbit change and calibration impact have been well characterized in previous studies through the use of regularly scheduled lunar observations. Further, the crosstalk correction was implemented in the Earth view (EV) images and quantified the improvements of the same. However, improvements remained desirable on several fronts. Firstly, the effectiveness of the correction needed to be analyzed spatially and radiometrically on several scenes. Also, the temporal aspect of the correction had to be investigated in a rigorous manner. In order to address these issues, a one-orbit analysis was performed on the Level 1A (L1A) scene granules over a ten year period from 2003 to 2012. Results have been quantified statistically and show a significant reduction of image striping, as well as removal of leaked signal features from the neighboring bands. Statistical analysis was performed by analyzing histograms of the one-orbit granules at a scene and detector level before and after correction. The comprehensive analysis and results reported in this paper will be very helpful to the scientific community in understanding the impacts of crosstalk correction on various scenes and could potentially be applied for future improvements of band 27 calibration and, therefore, its retrieval for the Level 2 (L2) geophysical parameters.

9218-20, Session 5

Terra's role in improving on-orbit calibration approaches

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The Terra platform enters its teenage years with an array of accomplishments but also with the potential to do much more. Efforts continue to extend the Terra data record to make its data more valuable by creating a record length that allows examination of inter annual variability, observe trends on the decadal scale, and gather statistics relevant to the define climate metrics. All five instruments on Terra continue to perform meritoriously. Continued data from Terra's complementary instruments will play a key role in creating the data record needed for scientists to develop an understanding of our climate system. Terra's suite of instruments: ASTER (contributed by the Japanese Ministry of Economy and Trade and Industry with a JPL-led US Science Team), CERES (NASA LaRC – PI), MISR (JPL – PI), MODIS (NASA GSFC), and MOPITT (sponsored by Canadian Space Agency with NCAR-led Science Team) are providing an unprecedented 81 core data products. The annual demand for Terra data remains with >120 million files distributed in 2011 and >157 million in 2012. More than 1,100 peer-reviewed publications appeared in 2012 using Terra data bringing the lifetime total >7,600. Citation numbers of 21,000 for 2012 and over 100,000 for the mission's lifetime.

The power of Terra is in the high quality of the data calibration, sensor characterization, and the inter-consistency of the data from its instruments. The combination of high quality instruments and their >14-year history allows calibration and validation scientists the opportunity to evaluate both the sensors as well as the methods for on-orbit calibration. This work highlights some of those accomplishments with an emphasis on the three imagers on Terra (ASTER, MISR, and MODIS) and vicarious approaches relying on in-situ measurements. Results from these sensors and the opportunity to evaluate cross-calibration approaches for simultaneous views give confidence in the application of these methods to other sensors impacting future sensor designs, on-ground testing approaches, and validation methods for Terra's data products.

9218-21, Session 5

Terra mission operations: launch to the present (and beyond)

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The Terra satellite, flagship of NASA's long-term Earth Observing System (EOS) Program, was launched in December 1999. Formerly "EOS AM-1", Terra continues to provide useful earth science observations well past its 5-year design lifetime. Barring unforeseen problems, it will surpass the 15-year coverage requirement for the three satellites in the original AM series, AM-1, AM-2, and AM-3; this is most fortunate since the AM-2 and AM-3 missions were eliminated due to budget cuts.

This paper describes the evolution of Terra operations, including challenges and successes in the 14+ years since launch and the steps taken to maintain the high level of science return and spacecraft longevity. Some challenges were due to predicted normal degradation of components associated with aging while others were environmental (such as the increasing level of orbital debris). The science and operations teams worked cooperatively to resolve the challenges and adjust operations as needed. Terra today retains all of its observing capabilities (except SWIR) despite its age. There have been many improvements in the ground systems enabling more efficient operations.

Working cooperatively with the Terra science and instrument teams, including NASA's international partners, the mission operations team has successfully kept the Terra operating continuously, with 99.3% (average) data recovery. In addition to science research, Terra data are used for operational applications, e.g., disaster and fire monitoring and management. Today, the number of low-cost direct broadcast receiving stations around the world utilizing Terra data continues to increase.

The paper will also briefly describe Terra concepts for future operations.

9218-22, Session 5

Evaluation of TERRA/ MISR's detector-based calibration from nearly 15 years of flight data

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The Multi-angle Imaging Spectrometer (MISR) was launched on-board NASA's Terra spacecraft in December 1999. The radiometric calibration of the instrument has since been maintained by a combination of preflight test results, "vicarious" field-campaigns, and bi-monthly deployment of the instrument's on-board calibrator (OBC). Preflight testing was invaluable at providing initial estimates of the pixel and band-relative calibrations, as well providng spectral characterization of the instrument response. The in-flight absolute radiometric scale is tied to a "vicarious calibration" field-campaign conducted at Lunar Lake, Nevada in 2001, which included underflights by the airborne sensor AirMISR. Maintenance of absolute radiometric accuracy over the life of the mission makes use of a novel detector-based approach. The MISR on-orbit calibration system consists of two Spectralon calibration panels and several sets of radiation-resistant photodiodes filtered to the MISR spectral bands (446, 558, 672, and 866 nm). When deployed, the panels are viewed by both the MISR cameras as well as the calibration photodiodes. These calibration sequences have been executed on a bimonthly basis throughout the mission. The Spectralon panels have remained stable on-orbit, due to a vacuum-bake procedure used to eliminate hydrocarbon contamination. The calibration is, however, traceable to the photodiode-measured radiance. Stability of these has been confirmed observations of homogeneous, stable Earth targets (e.g., large deserts). This paper summarizes the results of the MISR radiometric calibration, as now understood following nearly 15 years on-orbit. Included in the analyses are comparisons of MISR observations with data from other well-calibrated sensors, including MODIS, SeaWiFS, and CERES.

9218-23, Session 5

Status of Terra MODIS operation, calibration, and performance

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Since launch in December 1999, Terra MODIS has successfully operated for nearly 15 years, making continuous observations for studies of key geophysical parameters of the earth's system of land, ocean, and atmosphere, and their changes over time. The quality of MODIS data products relies on dedicated effort to monitor and sustain instrument health and operation, to calibrate and update sensor parameters and properties, and to maintain and improve calibration algorithms. MODIS observations are made in 36 spectral bands, covering wavelengths from visible to long-wave infrared. The reflective solar bands (1-19 and 26) are calibrated by a solar diffuser panel and regularly scheduled lunar observations. The thermal emissive bands (20-25 and 27-36) calibration is referenced to an on-board blackbody source. On-orbit changes in the sensor spectral and spatial characteristics are determined by a spectroradiometric calibration assembly. This paper provides an overview of Terra MODIS 15-year on-orbit operation and calibration activities and implementation strategies. It presents and summarizes sensor on-orbit performance derived from its telemetry, on-board calibrators, lunar observations, and reference ground targets. Also discussed in this paper are changes in sensor characteristics, corrections applied to maintain level 1B data quality, lessons learned, and efforts for future improvements.

9218-24, Session 5

Retrieval algorithm development and product validation for TERRA/MOPITT

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Satellite observations of tropospheric carbon monoxide (CO) are exploited in diverse atmospheric science applications including air quality studies, chemical weather forecasting and the characterization of CO emissions through inverse modeling. The TERRA / MOPITT (Measurements of Pollution in the Troposphere) instrument incorporates a set of gas correlation radiometers to observe CO simultaneously in both a thermal-infrared (TIR) band near 4.7 µm and a near-infrared (NIR) band near 2.3 µm. This multispectral capability is unique to MOPITT. The MOPITT retrieval algorithm for vertical profiles of CO has been refined almost continuously since TERRA was launched at the end of 1999. MOPITT 'Version 6' products became available in 2013. Algorithm enhancements are the result of ongoing analyses of instrument performance, improved radiative transfer modeling, and systematic comparisons with correlative data, including surface-based measurements, in-situ profiles measured from aircraft and products from other satellite instruments. This presentation will describe the methods used to quantitatively evaluate MOPITT CO profiles and their limitations. As the satellite instrument with the longest record for CO, methods for quantifying the long-term stability of the MOPITT record are becoming increasingly important.

9218-25, Session 6

On-orbit stability and performance of the Clouds and Earth's Radiant Energy System (CERES) Instruments onboard the Aqua and Terra Spacecraft

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The Clouds and Earth's Radiant Energy System (CERES) instruments onboard the Terra and Aqua spacecraft are part of the NASA Earth Observing System (EOS) constellation to make long-term observations of the earth. CERES measures the earth-reflected shortwave energy as well as the earth-emitted thermal energy, which are two components of the earth's radiation energy budget. These measurements are made by five instruments- Flight Models (FM) 1 and 2 onboard Terra, FMs 3 and 4 onboard Aqua and FM5 onboard Suomi NPP. Each instrument comprises three sensors that measure the radiances in different wavelength bands- a Shortwave channel that measures in the 0.3 to 5 micron band, a Total channel that measures all the incident energy (0.3- >100 microns) and a Window channel that measures the water-vapor window region of 8 to 12 microns. The stability of the sensors is monitored through on-orbit calibration and validation activities. On-orbit calibration is carried out using the Internal Calibration Module (ICM) that consists of a tungsten lamp, blackbodies, and a solar diffuser known as the Mirror Attenuator Mosaic (MAM). The ICM calibration provides information about the stability of the sensors' broadband radiometric gains on-orbit. Several validation studies are conducted in order to monitor the behavior of the instruments in various spectral bands. The CERES Edition-4 data products for FM1-FM4 incorporate the latest corrections to the sensor responses using the calibration techniques. In this paper, we present the on-orbit performance stability as well as some validation studies used in deriving the CERES Edition-4 data products from all four instruments.

9218-26, Session 6

Vicarious calibration of Terra/ASTER/VNIR with desert scenes together with cross calibration

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Vicarious calibration of Terra/ASTER/VNIR with desert scenes is presented together with cross calibration through comparisons with MODIS, MISR, etc. which are onboard the same satellite, Terra as well as Landsat ETM+ which is onboard the different satellite, Landsat.

It is found that there is discrepancy between onboard calibration data derived Radiometric Calibration Coefficient: RCC and vicarious calibration data derived RCC. On the other hand, cross calibration data derived RCC shows much closer to the vicarious RCC rather than onboard RCC through trend analysis. Therefore, it is concluded that RCC which is applied for Level 1 processing should be determined with vicarious RCC corrected onboard RCC.

9218-27, Session 6

ASTER/TIR vicarious calibration activities in US and Japan validation sites for 14 years

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The ASTER instrument onboard the NASA's Terra satellite launched in December 1999 has three subsystems divided by the spectral regions. ASTER thermal infrared (TIR) subsystem has five TIR bands with a spatial resolution of 90 m. Since March 2000 after the initial checkout period, many vicarious calibration (VC) experiments have been conducted for ASTER/TIR in lakes such as Lake Tahoe (NV/CA), Salton Sea (CA), and Lake Kasumigaura (Japan), and in dry lakes such as Railroad Valley (NV), Alkali Lake (NV), and Coyote Lake (CA). In the present paper, 307 VC matchup data obtained by three organizations were analyzed. Overall results show that a typical difference between the at-sensor radiance acquired by onboard calibration (OBC) and that predicted by VC is about 0.5 to 1 K in the water sites and about 1 to 2 K in the land sites. The results of the responsivity analysis indicate that VC is well tracking the responsivity changes measured by OBC, though the recent discrepancy at band 10 should be investigated with more VC results. The results of the offset analysis indicate that the short term calibration (STC) which is performed at a blackbody temperature of 270 K before every Earth observation has worked normally. It is therefore concluded that the ASTER/TIR instrument has been keeping the designed accuracy (1 K for the temperature range of 270 to 340 K) since the launch.

9218-28, Session 6

Review of Terra MODIS thermal emissive band radiometric performance evaluation

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The EOS Terra satellite will reach its 15th anniversary on-orbit in December 2014, with the MODIS instrument "first light" 15th anniversary following on February 24, 2015. The MODIS instrument has proven to be an enduring work horse, providing high quality radiances in all spectral bands. Though some detectors have fallen below SNR thresholds over the years, the vast majority of spectral bands continue to provide high quality L1B data for use in science algorithms supporting global climate research.

Radiometric accuracy of the Terra MODIS thermal emissive bands (TEB) has been assessed using various approaches over the years, including aircraft underflights, inter-satellite comparisons, and ground based instruments. All of these approaches have merit and are complementary to one another. Early in the lifetime of Terra, NASA ER-2 aircraft underflights revealed that TEB window bands are well calibrated and performing within accuracy specifications; atmospheric bands are more difficult to evaluate from the aircraft platform because of unsampled atmosphere above the aircraft level. Nevertheless, the ER-2 underflights indicated that, with the likely exception of LWIR CO2 bands that are subject to optical crosstalk, the TEB atmospheric bands were likely within or nearly within the accuracy specification. Beginning in 2007, MetOp-A IASI observations were used to evaluate Terra MODIS TEB L1B performance through SNO-based comparisons. These inter-satellite comparisons have demonstrated the radiometric stability of the MODIS TEB performance over the 2007-2013 timeframe. Additionally, it has been found that an effective spectral shift minimizes scene temperature dependence of MODIS-IASI comparisons for TEB.

9218-29, Session 6

In-flight validation of the mid and thermal infrared products from ASTER and MODIS on the Terra and Aqua platforms using the Lake Tahoe and Salton Sea automated validation sites

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In December 1999 NASA's first Earth Observation System platform (Terra) was launched into earth orbit. Five instruments are mounted on the platform and these are being used to produce a set of standard data products for the scientific community. Two of the instruments: the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the Moderate Resolution Imaging Spectroradiometer (MODIS) produce standard products that utilize data acquired in the mid (3-5 um) and thermal infrared part of the spectrum (7-14 um). Such products include radiance at sensor, radiance at surface, surface temperature and surface emissivity. In 2002 a second MODIS instrument was launched on the Aqua platform and since then other instruments with similar capabilities to MODIS such as the Visible Infrared Imaging Suite (VIIRS) have been launched on other platforms. All these instruments generate similar products that are used for a wide variety of applications and it is essential that they are validated to ensure the instruments and the standard product algorithms are functioning correctly.

In order to validate as well as cross compare products both NASA we have established two automated validation sites where the necessary measurements for validation are made every few minutes on a continuous basis. One of these sites is located at Lake Tahoe CA/NV, USA. L. Tahoe is ideally suited for validation of mid and thermal infrared data for several reasons including its size, homogeneity, elevation, accessibility and composition. In order to use L. Tahoe for validation, 4 buoys have been deployed. Each buoy includes a custom-built highly accurate (50mK) radiometer measuring the surface skin temperature and several bulk temperature probes that trail behind the buoy. Each buoy includes a logging system with dial-up cellular access. Each buoy also has two full meteorological station measuring wind speed, wind direction, relative humidity and net radiation. All the measurements are made every few minutes and downloaded hourly via a cellular modem. The buoy measurements are supplemented with a variety of atmospheric measurements made on-shore. Results from the validation of the mid and thermal infrared data from the ASTER and MODIS (Terra and Aqua) instruments will be presented.

9218-30, Session 7

Corrections to MODIS Terra calibration and polarization trending derived from ocean color products

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Remotely sensed ocean color products require an extraordinary high level of radiometric accuracy for the top-of-atmosphere (TOA) radiances, on the order of 0.5% or better. Due to incidents both prelaunch and on-orbit, meeting this requirement has been a consistent problem, especially in the later part of the Terra mission. The NASA Ocean Biology Processing Group has developed an approach to correct the TOA radiances of MODIS Terra using spatially and temporally averaged ocean color products from other ocean color sensors (SeaWiFS for the early part of the Terra mission, MODIS Aqua for the later part). We will present the approach and discuss the latest results from this approach. Of particular interest is the change in polarization sensitivity of the instrument, which has been significant in the short wavelength bands.

9218-31, Session 7

Comparison of coincident MODIS and MISR reflectances over the 15-year period of EOS Terra

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Terra is the flagship of NASA's Earth observing systems (EOS), carrying five sensors (ASTER, CERES, MISR, MODIS, and MOPITT), which have been providing high-quality global observations for nearly 15 years. MODIS has 20 reflective solar bands (RSB), which are calibrated using a solar diffuser (SD) with its degradation tracked by a solar diffuser stability monitor (SDSM). MODIS scheduled lunar roll observations and vicarious data from pseudo-invariant sites are used to characterize the scan-angle dependence for the MODIS RSB. The Multi-angle Imaging Spectroradiometer (MISR) makes near simultaneous measurements at nine view angles spreading out in the forward and backward directions along the flight path including nadir in four spectral bands (blue, green, red and near-infrared). MISR calibration efforts are based on a combination of preflight, onboard, and field vicarious measurements. This study compares coincident MODIS and MISR near-nadir reflectances over their entire mission to examine the calibration stability and consistency of the two instruments. Reflectances from low to high radiance levels are used to characterize the calibration performance based on data obtained from ocean, desert and Antarctic snow surfaces.

9218-32, Session 7

Cross-calibration of Earth Observing System Terra satellite sensors MODIS and ASTER

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The Advanced Spaceborne Thermal Emissive and Reflection Radiometer (ASTER) and Moderate Resolution Imaging Spectrometer (MODIS) are two of the five sensors onboard the Earth Observing System's Terra satellite. These sensors share many similar spectral channels while having much different spatial and operational parameters. ASTER is a tasked sensor and sometimes referred to a zoom camera of the MODIS that collects a full-earth image every one to two days. It is important that these sensors have a consistent characterization and calibration for continued development and use of their data products. This work uses a variety of test sites to retrieve and validate intercalibration results. The refined calibration of Collection 6 of the Terra MODIS data set is leveraged to provide the up-to-date reference for trending and validation of ASTER. Despite differences in spectral band properties and spatial scales, ASTER-MODIS is an ideal case for cross-calibration since the sensors have nearly identical views and acquisitions times and therefore can be used as a baseline of intercalibration performance of other satellite sensor pairs.

9218-33, Session 7

The absolute radiometric calibration of Terra imaging sensors: MODIS, MISR, and ASTER

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The Terra spacecraft contains five Earth-observation instruments, three of which are multispectral imaging sensors that complement each other in spectral and spatial coverage. The Moderate Resolution Imaging Spectroradiometer (MODIS) has 36 channels ranging from 0.4–14.4 um, with spatial resolutions of 250, 500, and 1000 m. The Multi-angle Imaging SpectroRadiometer (MISR) uses individual imaging sensors to view the Earth at nine discreet angles. Each radiometer has four channels in the VNIR, and the nadir-viewing camera has a spatial resolution of 275 m. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) was designed with fourteen bands ranging from 0.5–11.6 um. It is the high-resolution sensor on Terra, with a spatial resolution of 15 m in the VNIR, and 30 m in the SWIR. This work describes the vicarious techniques used to perform the absolute radiometric calibration of MODIS, MISR, and ASTER in the solar-reflective region (0.4–2.5 um). It includes the reflectance-based approach, which uses ground-based personnel to make in situ measurements during the time of overpass. It also includes more recent results that were obtained using the University of Arizona's automated Radiometric Calibration Test Site (RadCaTS) at Railroad Valley, Nevada. In addition to the absolute radiometric calibration of Terra sensors, RadCaTS is used to perform the cross calibration of MODIS, MISR, and ASTER with Landsat 7 ETM+ and Landsat 8 OLI.

9218-34, Session 8

Validation of spectral radiance assignments to integrating sphere radiance standards for the Advanced Baseline Imager

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The Advanced Baseline Imager (ABI) is the next generation imaging sensor for NOAA's operational meteorological satellites in geostationary orbit. One pathway for traceability of the visible and near infrared radiometric response for ABI is to a 1.65 m diameter integrating sphere source standard of spectral radiance. This source illuminates the full entrance pupil via the ABI Earth-view port, thus determining the absolute spectral radiance responsivity in the visible and shortwave infrared. The spectral radiance values of the large sphere are assigned by Exelis using a double monochromator and a 15.24 cm diameter integrating sphere source standard that is calibrated by NIST. As part of the ABI program, Exelis was required by NASA to have the spectral radiance values assigned by Exelis to the large sphere be validated by NIST. Here we report the results of that activity, which took place in April, 2013. During the week of April 8, Exelis calibrated the 1.65 m diameter sphere at all 24 levels that correspond to the ABI calibration protocol. During the week of April 15, the NIST validation exercise for five selected levels took place. NIST deployed a portable spectral radiance source, a filter radiometer restricted to the visible and near-infrared, and two spectroradiometers

that covered from 350 nm to 2500 nm. The NIST sphere source served as the validation standard. The comparison results, which are reported at the ABI bands, agreed to within the combined uncertainties. We describe the methodology, results, and uncertainty estimates related to this effort.

9218-35, Session 8

Improved thermal-vacuum compatible flat plate radiometric source for system-level testing of optical sensors

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In this work, development of a fiber-optically coupled, vacuum-compatible, flat plate radiometric source applicable to the characterization and calibration of remote sensing optical sensors in situ in a thermal vacuum chamber is described. The original flat plate radiometric source configuration's performance was presented at the 2009 SPIE1. Following the original effort, design upgrades were incorporated in order to improve radiometric throughput and uniformity. Results of thermal and radiometric performance, with incorporated upgrades, of a flat plate illumination source in a temperature-controlled vacuum chamber operating at liquid nitrogen temperature are presented. Applications, including use with monochromatic tunable laser sources for the end-to-end system-level testing of large aperture sensors, are briefly discussed.

9218-36, Session 8

Diffuser properties and according performance in BSDF and spectral features in space application

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A diffuser is a core element of calibration units in earth observation instruments. Its performance influences significantly the achievable accuracy of scientific observations.

However, the performance, in particular the Bi-Directional Scattering Function BSDF and speckle induced non-uniformities in the recorded earth observation spectra, depends on several parameters, such as surface properties, instrument configuration, observational conditions and further. This paper describes experimental activities to achieve a better understanding about the interaction between diffuser properties and performance with regards to its scattering behaviour and speckle generation on earth observation instruments.

For this purpose a set of 24 diffusers with defined surface properties, i.e. mainly the roughness related parameter R_q with a value between 0.5µm and 3.2µm, have been manufactured,. These components were systematically investigated, BSDF measurements were performed in the "Absolute Radiometric Calibration Facility ARCF" at TNO Delft in the Netherlands, a unique setup for the characterisation and calibration of optical components for space applications. A further dedicated setup was used for speckle measurements and the determination of spectral features. The achieved results show systematic patterns in the relation between surface property and performance in BSDF and speckle generation. However, our experimental results deviate from existing theoretical models, which for instance predict a significant change in BSDFwith only a slight variation in surface roughness. The measurements presented in this paper suggest a far lesser dependency and therefore indicate the necessity of further development of existing theoretical models. The derived empirical model will provide an additional data base for such further developments, furthermore it will simplify the definition and design of diffuser properties for future earth observation instruments

9218-37, Session 8

BRDF characterization of solar diffuser for JPSS J1 using PASCAL

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The Visible/Infrared Imaging Radiometer Suite (VIIRS) is a key sensor on the Suomi National Polar-orbiting Partnership (NPP) satellite as well as the upcoming Joint Polar Satellite System (JPSS). VIIRS collects Earth radiometric and imagery data in 22 spectral bands from 0.4 to 12.5 ?m. Radiometric calibration of the reflective bands in the 0.4 to 2.5 ?m wavelength range is performed by measuring the sunlight reflectance from Spectralon®. Reflected sun light is directly proportional to the Bidirectional Reflectance Distribution Function (BRDF) of the Spectralon®. This paper presents the BRDF measurements of the Spectralon® for JPSS in the 0.4 – 1,63 ?m wavelength using PASCAL (Polarization And Scatter Characterization Analysis of Lambertian materials) with an uncertainty better than 1.2%. PASCAL makes absolute measurements of BRDF in an analogous fashion National Institute of Standards and Technology (NIST) Spectral Tri-function Automated Reflectance Reflectometer (STARR) facility. BRDF is calculated on the basis of the measured incident power, reflected power and geometric factors eliminating the need for a standard. The detector rotates about the sample in the plane defined by the source beam and the azimuth rotation of the sample. Unique additional features of this instrument include the ability to vary the sample elevation and roll / clock the sample about its normal allowing measuring BRDF in the as use geometry. A description of PASCAL, validation and the BRDF results of the Solar Diffuser will be presented. Non-uniformity of Spectralon® that is part dependent has also been observed.

9218-38, Session 8

JPSS solar diffuser stability monitor response to sun angle of incidence

Vijay Murgai, Kristie Yu, Eugene D. Kim, Neil R. Nelson, Raytheon Space & Airborne Systems (United States); James K. McCarthy, Stellar Solutions Inc. (United States)

The Visible/Infrared Imaging Radiometer Suite (VIIRS) is a key sensor on the Suomi National Polar-orbiting Partnership (NPP) satellite in orbit as well as for the upcoming Joint Polar Satellite System (JPSS). VIIRS collects Earth radiometry and imagery in 22 spectral from 0.4 to 12.5 ?m. Radiometric calibration of the reflective bands in the 0.4 to 2.5 ?m wavelength range is performed by measuring the sunlight reflectance from Solar Diffuser Assembly (diffuser is Spectralon®). Spectralon® is known to solarize due to sun UV exposure at the blue end of the spectrum (~0.4 – 0.6+ ?m) as seen by laboratory tests as well as on orbit data from MODIS and NPP. VIIRS uses a Solar Diffuser Stability Monitor (SDSM) to monitor the change in the Solar Diffuser reflectance in the 0.4 – 0.94 ?m wavelength range to correct the calibration constants. The SDSM measures the ratio of sun light reflecting from the Solar Diffuser to a direct view of the sun. As the intensity of the light reaching the SDSM in both Solar Diffuser view and sun view is a function of the sun's angle of incidence (AOI), the SDSM response to sun AOI has to be characterized.

This paper presents details of the test setup including an extended collimated source simulating the sun across all SDSM bands. The pre-launch characterization results for the J1 SDSM are presented. Comparison with NPP on orbit yaw maneuver SDSM results shows similar behavior demonstrating that the J1 test successfully characterized the SDSM response to sun AOI.

9218-39, Session 8

Development of low optical cross talk filters for VIIRS for JPSS

Vijay Murgai, Derek Hendry, Raytheon Space & Airborne Systems (United States); Kevin R. Downing, Materion Barr Precision Optics & Thin Film Coatings (United States); Dave Carbone, Materion Corp. (United States); John R. Potter, Materion Barr Precision Optics & Thin Film Coatings (United States)

The Visible/Infrared Imaging Radiometer Suite (VIIRS) is a key sensor on Suomi National Polar-orbiting Partnership (NPP) satellite launched on October 28, 2011 into a polar orbit of 824 km nominal altitude and the JPSS sensors currently being built. VIIRS collects radiometric and imagery data of the Earth's atmosphere, oceans, and land surfaces in 22 spectral bands spanning the visible and infrared spectrum from 0.4 to 12.5 ?m. Interference filters assembled in 'butcher-block' arrays are used close to focal plane arrays for spectral definition. Out-of-band signal and out-of-band optical cross-talk was observed for bands in the 0.4 to 1 ?m range in testing of VIIRS for NPP. Optical cross-talk is in-band or out-of-band light incident on an adjacent filter or adjacent region of the same filter reaching the detector. Out-of-band optical cross-talk results in spectral and spatial 'impurities' in the signal and consequent errors in the calculated environmental parameters such as ocean color that rely on calculations based on combinations of signals from more than one band.

This paper presents results of characterization, specification, and coating process improvements that enabled production of filters with significantly reduced out of band light for JPSS J1 and subsequent sensors. Total transmission and scatter measurements at a wavelength within the pass band can successfully characterize filter performance prior to cutting and assembling into the butcher block assemblies. Coating and process development demonstrated performance on test samples followed by production of filters for J1 and J2. Results for J1 and J2 filters will be presented.

9218-40, Session 9

Landsat-8 Operational Land Imager on-orbit radiometric calibration and stability

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Landsat-8, with the Operational Land Imager on board, was launched In February 2013 and has been successfully operating on-orbit since then. A solar calibration mechanism with two characterized Spectralon solar diffusers is the primary on-orbit calibration device with nominally weekly usage; a lamp based system with 3 pairs of tungsten-halogen bulbs is also available for nominally daily acquisitions. Each device has a "pristine" article, that is used rarely to monitor the "working" article. Since launch these devices have tracked the performance of the OLI and have shown: (1) no measurable responsivity change as a function of position in orbit and (2) drifts in the OLI response of less than 1% per year. The largest change is about 0. 9 % change over the first year for band 1 (443 nm), All other bands changed by less than 0.3% over the first year and the rate of change is decreasing with time. Comparisons to other satellite sensor and ground observations indicates that the OLI radiometric calibration uncertainty is less than 5%.

9218-41, Session 9

On-orbit performance of the Landsat 8 Operational Land Imager

Esad Micijevic, U.S. Geological Survey (United States) and SGT, Inc. (United States); Kelly J. Vanderwerff, SGT, Inc. (United States); Pat L. Scaramuzza, U.S. Geological Survey (United States) and SGT, Inc. (United States); Julia A. Barsi, Raviv Levy, NASA Goddard Space Flight Ctr. (United States) and Science Systems and Applications, Inc. (United States)

The Landsat 8 satellite was launched on February 11, 2013 to systematically collect multispectral images for detection and quantitative analysis of changes on the Earth's surface. The collected data are stored at the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center and continue the longest archive of medium resolution Earth images.

As the primary imaging instrument onboard the satellite, the Operational Land Imager (OLI) continues the global Earth data record in solar reflective bands. It is a pushbroom sensor with nine spectral bands consisting of 69160 detectors distributed across 14 Sensor Chip Assemblies (SCA).

Earth scene data and calibration acquisitions, including images of the dark shutter, internal stimulation lamps, solar diffusers and Moon, are processed through the Image Assessment System (IAS) and the system's database is populated with the results. These statistics and parameters are input to online and offline analysis of the OLI radiometric performance.

This paper summarizes the OLI radiometric performance including the bias stability, the system noise, saturation and other artifacts observed in OLI data during the first 1.5 years on orbit.

9218-42, Session 9

Performance of the thermal infrared sensor onboard Landsat 8 over the first year on-orbit

Matthew Montanaro, Sigma Space Corp. (United States); Brian L. Markham, NASA Goddard Space Flight Ctr. (United States); Allen W. Lunsford, The Catholic Univ. of America (United States); Kelly J. Vanderwerff, SGT, Inc. (United States); Julia A. Barsi, Science Systems and Applications, Inc. (United States)

The Thermal Infrared Sensor (TIRS) has completed over one year in Earth orbit following its launch onboard Landsat 8 in February 2013. During that time, TIRS has undergone initial on-orbit checkout and commissioning and has transitioned to an operational Landsat payload obtaining 500+ Earth scenes a day. The instrument was radiometrically calibrated during pre-flight characterization testing. A relative adjustment was made to the calibration during the on-orbit checkout of the instrument based on data from the onboard calibration sources to account for instrument changes that occurred through launch.

The accuracy of the relative and absolute radiometric calibration depends in part on the stability of the instrument response over time. To monitor stability, TIRS routinely views its onboard calibration sources, which include a variable temperature blackbody and a port that allows the instrument to view deep space. The onboard calibration is validated by in situ measurements of large water bodies by instrumented buoys. In addition, the spacecraft is periodically slewed to image the moon across the field of view of TIRS. The moon provides a high contrast source which allows for studies of stray light and ghosting to be performed.

These on-orbit methods provide the means to characterize the TIRS instrument performance post-launch. Analyses of these datasets over the first year on orbit indicate that while, internally, the instrument itself is far exceeding the noise and stability requirements, both bands were mis-calibrated by at least 2K (@300K) and had higher than expected variability in the in situ validation data. This is likely due to stray light which is also causing banding in Earth scenes. An initial bias correction

was made on February 2014 and various approaches are being explored to correct the ghosting issues associated with the stray light.

9218-43, Session 9

Landsat 8 Operational Land Imager (OLI) detector to detector uniformity challenge and performance

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The Operational Land Imager (OLI) aboard the Landsat-8 satellite was rigorously radiometrically characterized prior to launch to assure absolute calibration that is NIST traceable. On orbit additional dedicated calibration collects are being made to continue monitoring and characterizing the OLI radiometric performance. In this paper we report on the OLI on-orbit uniformity performance, which is a natural extension of the absolute radiometric accuracy. Such performance characteristic in remote sensing instruments is assuring that the radiometric accuracy in low contrast images is preserved while avoiding non-uniformity artifacts in the produced radiometric product. The LDCM project science team working with the instrument teams developed a performance metric to monitor the uniformity performance. We will describe the uniformity performance metric and discuss associated error sources in obtaining the radiometric calibration parameters that impact the uniformity correction. We will compare the uniformity performance between solar diffuser observation and earth data.

9218-44, Session 9

The absolute radiometric calibration of the Landsat 8 Operational Land Imager using the reflectance-based approach and the Radiometric Calibration Test Site (RadCaTS)

Jeffrey S. Czapla-Myers, Nikolaus J. Anderson, College of Optical Sciences, The Univ. of Arizona (United States); Kurtis J. Thome, NASA Goddard Space Flight Ctr. (United States); Stuart F. Biggar, College of Optical Sciences, The Univ. of Arizona (United States)

Landsat 8 was launched on 11 February 2013, and it is the newest platform in the Landsat program. It contains two Earth-observing instruments, one of which is the Operational Land Imager (OLI). OLI includes an onboard radiometric calibration system that is used to monitor changes in its responsivity throughout the mission lifetime, and it consists of Spectralon solar diffuser panels as well as tungsten lamp assemblies. External techniques are used to monitor both OLI and its calibration system, and they include lunar views, side slither maneuvers of the satellite, and ground-based vicarious calibration. This work presents the absolute radiometric calibration results for Landsat 8 OLI that were obtained using two ground-based measurement techniques. The first is the reflectance-based approach, where measurements of atmospheric and surface properties are made during a Landsat 8 overpass, and it requires personnel to be on site during the time of measurement. The second uses the Radiometric Calibration Test Site (RadCaTS), which was developed by the Remote Sensing Group in the College of Optical Sciences at the University of Arizona so that radiometric calibration data can be collected without the requirement of on-site personnel. It allows more data to be collected annually, which increases the temporal sampling of trending results.

9218-45, Session 10

Chasing the TIRS ghosts: calibrating the Landsat 8 thermal bands

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The Thermal Infrared Sensor (TIRS) on board Landsat 8 has exhibited a number of anomalous characteristics that have made it difficult to calibrate. These anomalies include differences in the radiometric appearance across the black body pre and post launch, variations in the cross calibration ratios between detectors that overlap on adjacent arrays (resulting in banding) and bias errors in the absolute calibration that can change spatially/temporally. Several updates to the TIRS calibration procedures were made in the months after launch to attempt to mitigate the impact of these anomalies on flat fielding (cosmetic removal of banding and striping) and mean level bias correction. As a result banding and striping variations have been reduced but not eliminated and residual bias errors in band 10 should be less than 2 degrees for most targets but can be significantly more in some cases and are often larger in band 11. These corrections have all been essentially ad hoc without understanding or properly accounting for the source of the anomalies which were at the time unknown. This paper addresses the procedures that have been undertaken to; better characterize the nature of these anomalies, attempt to identify the source (s) of the anomalies, quantify the phenomenon responsible for them, and develop correction procedures to more effectively remove the impacts on the radiometric products. Our current understanding points to all of the anomalies being the result of internal reflections of energy from outside the target detector's field of view and often outside the telescope field of view onto the target detector. This paper will discuss how various members of the Landsat calibration team discovered the clues that led to how; these "ghosts" were identified, they are now being characterized, and their impact can hopefully eventually be corrected. This includes use of lunar scans to generate initial maps of influence regions, use of long path overlap ratios to explore sources of change and use of variations in bias calculated from truth sites to quantify influences from the surround on absolute bias errors.

9218-46, Session 10

Landsat-8 data processing evolution

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Shortly after Landsat-8 launched in February 2013, the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center began creating radiometrically and geometrically corrected products. In order to provide these products as soon as possible, the Level 1 Product Generation System (LPGS) was developed prior to launch based on instrument designs and testing prior to launch. While every effort was made to ensure the LPGS produces highly accurate products, some aspects of the sensors are difficult to characterize during testing on the ground. Examples of these characteristics include slight differences between individual detectors that make up the focal plane array, differences in the way the detectors view radiometric targets on the ground versus the way they view the Earth, and the accuracy of the measurements made on the ground. Once in orbit, more accurate measurements of some of these sensor characteristics improves processing parameters, resulting in improved quality of the final imagery.

This paper reviews the changes that have occurred to the processing of Landsat-8 data products which include parameter changes as well as some modifications to the processing system itself. These changes include: improved linearization of the data, both to parameters and the algorithm used for linearizing the data; improved radiance and

reflectance conversion coefficients; individual detector coefficients to improve uniformity; and geometric alignment coefficients to improve the geometric accuracy. These improvements lead to a reprocessing campaign that occurred in early in 2014.

9218-47, Session 10

European Space Agency (ESA) Landstat MSS/TM/ETM+ archive bulk-processing: processor improvements and data quality

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The Landsat program is a joint United States Geological Survey (USGS) and National Aeronautics and Space Administration (NASA) enterprise for Earth Observation (EO), that represents the world's longest running system of satellites for moderate-resolution optical remote sensing.

The European Space Agency (ESA) has acquired Landsat data over Europe through the ESA ground stations over the last 40 years, in co-operation with USGS and NASA.

A new ESA Landsat Multi-Spectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) processor has been developed. This enhanced processor aligns the historical Landsat products to the highest quality standards that can be achieved with the current knowledge of the instruments. The updated processor is mainly based on the USGS algorithm; however the ESA processor has some different features that are detailed in this paper.

Using this upgraded processor, ESA is currently performing for the first time a bulk-processing of its entire Landsat series MSS/TM/ETM+ historical archive to make all products available to users.

Current achievements include the processing and online distribution of approximately 290 000 new Landsat 5 TM high-quality products acquired at the Kiruna ground station between 1983 and 2011. The Landsat 5 TM bulk-processed products are made available for direct download after registration at: https://earth.esa.int/web/guest/pi-community/apply-for-data/fast-registration. The remainder of the ESA's Landsat data, dating back more than 40 years, will gradually become available for all users during the course of 2014.

The ESA Landsat processor algorithm enhancement, together with the results of the ESA archive bulk-processing, and an overview on the data quality on a subset of the Landsat 5 TM data are herein presented.

9218-48, Session 11

EUMETSAT programmes and plans

K. Dieter Klaes, Kenneth Holmlund, EUMETSAT (Germany)

EUMETSAT's mandate comprises the support of operational meteorology and climate monitoring. These goals are pursued with mandatory programmes, in the geostationary and sun-synchronous polar orbits. In the frame of optional programmes further tasks like altimetry and oceanography are fulfilled. In the frame of third party programmes, EUMETSAT provides data from other agencies' satellites to the user community. EUMETSAT is currently operating the Meteosat-7 and three satellites of the Second Generation of Meteosat (Meteosat Second Generation (MSG-1, MSG-2 and MSG-3)), named Meteosat-8, Meteorsat-9 and Meteosat-10 in orbit. The MSG-4 satellites is being prepared for a launch in 2015. It is planned to store the spacecraft in orbit after successful commissioning. The MSG Programme has been developed in co-operation between EUMETSAT and ESA. In parallel, EUMETSAT has developed jointly with ESA, NOAA and CNES the EUMETSAT Polar System (EPS). Metop-A, the first of a series of three satellites, is in orbit since 19th October 2006. Metop-A provides operational services from the mid-morning polar orbit in the frame of the Initial Joint Polar System (IJPS) with the US. Metop-B, the second satellite of a series of three was launched the 18 September 2012, and is now the prime satellite after successful commissioning. Metop-A services are continued in parallel operations. The EUMETSAT Advanced Retransmission Service (EARS) continued and extended its operational services and provides observations from partner HRPT (High Resolution Picture Transmission) stations. EUMETSAT's first optional programme, making use of the data from the Jason-2 satellite, provides operational Ocean Surface Topography information services since summer 2008. Jason-2 is a joint programme with CNES, NOAA and NASA. In a follow on Jason-3 optional programme the Jason-3 satellite is prepared for a lunch in spring 2015. The development of Meteosat Third Generation (MTG) and the preparations for EPS-SG (EPS Second Generations) are ongoing. The MTG programme is now in Phase C and the development is proceeding. In the frame of the Copernicus Programme (formerly GMES (Global Monitoring for Environment and Security)) EUMETSAT will operate the marine part of the Sentinel-3 satellites which complements the Ocean services. The implementation of the Ground Segment and the preparations for service after the planned launch end 2014/begin 2015 are underway.

9218-49, Session 11

Copernicus Sentinel-2 Mission: products, algorithms, and CAL/VAL

Ferran Gascon, European Space Agency (Italy)

The Copernicus programme is a European initiative for the implementation of information services dealing with environment and security, based on observation data received from Earth Observation (EO) satellites and ground based information. Within this context, ESA is responsible in particular, for the implementation of the Copernicus Sentinel missions, feeding the Copernicus services with operational EO data. The Sentinel-2 optical high-resolution imaging mission will be devoted to the operational and systematic monitoring of land and coastal areas.

To maximize the products suitability and readiness to downstream usage for the majority of applications, the Sentinel-2 Payload Data Ground Segment (PDGS) will systematically generate, archive and distribute Level-1C products, which will provide Top-of-Atmosphere (TOA) reflectance images, orthorectified using a global Digital Elevation Model (DEM) and projected on Universal Transverse Mercator (UTM) coordinate system. A Level-1B product will also be available for expert users, providing radiance images in sensor geometry together with an appended geometric model.

Additionally, a complementary atmospheric correction and enhanced cloud screening algorithm is being prototyped. This processor will allow converting the Level-1C TOA reflectance image into Bottom-of-Atmosphere (BOA) reflectance. The processor will be provided as plug-in software of the Sentinel-2 Toolbox that will run on user side.

During the operational phase, the Sentinel-2 Mission Performance Centre (MPC), as integrating part of the mission ground segment, will be in charge of ensuring that mission performances are met in terms of data quality through the calibration and validation activities.

9218-50, Session 11

The CarbonSat candidate mission: imaging greenhouse gas concentrations from space

Bernd Sierk, Armin Loescher, Yasjka Meijer, Jerôme C. Caron, Jean-Loup Bézy, European Space Agency (Netherlands)

CarbonSat is a proposed Earth observation mission, which was selected in 2012 as one of two candidates for becoming the European Space Agency's (ESA) eighth Earth Explorer (EE8). It is currently undergoing parallel feasibility studies (phase A) performed by two industrial consortia. CarbonSat aims at contributing to the understanding of climate feedback and forcing mechanisms and to the discrimination of natural and anthropogenic greenhouse gas fluxes. To achieve these objectives the instrument will quantify and monitor the spatial distribution of carbon dioxide (CO2) and methane (CH4). It will deliver global data sets of dry air column-averaged mixing ratios of these gases with high precision and accuracy (0.5 ppm for CO2 and 5 ppb for CH4) and provide global coverage every 12 days above 40 degrees latitude at a spatial resolution of 2 x 3 km2. These products are inferred from observations of Earth spectral radiance and solar irradiance at high to medium spectral resolution (0.1-0.55 nm) in the Near Infrared (747-773 nm) and Short Wave Infrared (1590-1675 nm and 1925-2095 nm) spectral regions. The combination of high spatial resolution and global coverage requires a swath width larger than 180 km for three spatially co-aligned push-broom imaging spectrometers. The targeted product accuracy translates into stringent radiometric, spectral and geometric requirements for the instrument. The presentation will review the system requirements derived from the demanding mission objectives and report preliminary results of the feasibility studies. It will highlight the key components of the instrument, focusing on the optical conceptual design, and address the identified critical performance aspects.

9218-51, Session 11

Design validation for ICESat2 space-based laser transmitter

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Fibertek is under contract from NASA Goddard to build four space qualified laser transmitters for the ICESat-2 (Ice, Cloud, and land Elevation Satellite) program, a second generation orbiting laser altimeter. Pertinent laser parameters driving the design included laser wall plug efficiency, laser reliability, a relatively narrow linewidth with wavelength tunability, high beam quality (M2<1.6), short pulsewidths (<1.5ns), and energy scalable from 250 µJ to 900µJ in predefined steps. The laser design employs fiber coupled 880nm diodes and end pump NdYVO4 slabs as the gain medium in a master oscillator/power amplifier (MOPA) architecture with an LBO second harmonic generator (SHG). Following the SHG is a telescope that sets the final beam size and divergence requirements. The first laser built will be the Integration and Test Laser (ITL) used for qualification of the design. The ITL will set the baseline parameters for the flight laser builds. The ITL will also validate the design for the telescope and will be subjected to the full environmental testing required for a space hardened flight laser. Environmental testing includes vibration, thermal vacuum conditions, and electromagnetic interference (EMI). Our presentation will address the measured laser parameters from ITL as compared to the as designed laser.

9218-52, Session 11

The GeoTASO airborne spectrometer project

James W. Leitch, Thomas Delker, William S. Good, Lyle Ruppert, Ball Aerospace & Technologies Corp. (United States); Kelly Chance, Xiong Liu, Caroline R. Nowlan, Harvard-Smithsonian Ctr. for Astrophysics (United States); Scott J. Janz, Nickolay A. Krotkov, Kenneth Pickering, NASA Goddard Space Flight Ctr. (United States); Matthew G. Kowalewski, Goddard Earth Sciences and Technology Ctr. (United States); Jun Wang, Univ. of Nebraska-Lincoln (United States)

The NASA ESTO-funded Geostationary Trace gas and Aerosol Sensor Optimization (GeoTASO) development project demonstrates a reconfigurable multi-order airborne spectrometer and tests the performance of spectra separation and filtering on the sensor spectral measurements and subsequent trace gas and aerosol retrievals. The activities support mission risk reduction for the UV-Vis air quality measurements from geostationary orbit for the TEMPO and GEMS missions. The project helps advance the retrieval algorithm readiness through retrieval performance tests using scene data taken with varying sensor parameters. We report initial test results of the project, which include lab testing of the sensor performance and flight data analysis on sensor performance and data quality for use in atmospheric retrievals of trace gases, ozone, and aerosols.

9218-53, Session 11

Remote sensing capabilities of the GeoCAPE Airborne Simulator

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The GEOstationary Coastal and Air Pollution Events (GeoCAPE) Airborne Simulator (GCAS) is a hyper-spectral imaging instrument built at NASA's Goddard Space Flight Center as a technology demonstrator for the atmospheric science study group of GeoCAPE and potential validation instrument for NASA's Tropospheric Emissions: Monitoring Pollution (TEMPO) mission. The dual channel system is comprised of two Offner design spectrometers coupled with wide-field refractive foreoptics in order to make high altitude remote sensing observations of tropospheric and boundary layer pollutants and visible imagery for cloud and surface information. The instrument has participated in one flight campaign in Houston, TX as part of the Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) in September 2013. An overview of the instrument's design, laboratory characterization, and preliminary slant column retrievals of nitrogen dioxide (NO2), ozone (O3), and formaldehyde (HCHO) during the DAQ campaign will be provided in this paper.

9218-54, Session 12

Monitoring the Terra and Aqua MODIS RSB calibration using the scattered light from the nadir-port

Amit Angal, Science Systems and Applications, Inc. (United States); Xiaoxiong J. Xiong, NASA Goddard Space Flight Ctr. (United States); Xu Geng, Junqiang Sun, Sigma Space Corp. (United States)

MODIS is currently onboard NASA's EOS Terra and Aqua spacecraft launched on December 18, 1999 and May 4, 2002 respectively. MODIS reflective solar bands (RSB) are calibrated on-orbit using solar illumination reflected from its onboard solar diffuser (SD). The solar diffuser stability monitor (SDSM) is designed to track the on-orbit degradation of the SD via alternate observations of the Sun and SD. A wavelength-dependent degradation pattern is observed for both MODIS instruments with a faster degradation rate observed at shorter wavelengths. The UV exposure of the SD to sunlight and the scattered light (the sunlight reflected from top of the atmosphere) through the instrument nadir port contributes to its reflectance degradation. The scatter off the diffuser onto the scan mirror is in the forward direction, whereas the scatter off the diffuser onto the SDSM scan mirror is in the backward direction. A methodology is formulated to track the MODIS SD degradation using the scattered light through the nadir-port and comparing the result with the SD degradation as measured by the SDSM. In this study, multiple orbits from a given day of each month are processed to obtain a SD response to the nadir-port illumination. A reasonable agreement is observed between the SD degradation

estimates derived from both view-angles. This methodology also serves as an alternative means of tracking the SD degradation on a near-continuous basis.

9218-55, Session 12

Progress on Alternative Method of the on-orbit RVS Characterization for MODIS Reflective Solar Bands

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MODIS Reflective Solar Bands (RSB) are calibrated on-orbit using onboard calibrators, including a Solar Diffuser (SD), a Solar Diffuser Stability Monitor (SDSM), and a Spectroradiometric Calibration Assembly (SRCA). A Space View (SV) port is used to provide a background reference, and also facilitate near monthly lunar observations via a spacecraft roll. In every scan, the earth's surface, SV and onboard calibrators are viewed via a two sided scan mirror, whose reflectance depends on the angles of the incidence (AOI) as well as the wavelength of the incident light. Response versus Scan angle (RVS) is defined as a dependence function of the scan mirror's reflectance over AOI. An initial RVS for each RSB was measured prelaunch for both Terra and Aqua MODIS. Algorithms have been developed to track the on-orbit RVS variation using the onboard calibrators, supplemented with the Earth View (EV) response from pseudo-invariant desert targets obtained at different AOI. The current approach, as implemented in Collection 6 (C6), uses EV responses from the Libyan Desert sites to track the on-orbit RVS change. Its dependence on the temporal stability of the desert sites is one of the primary limitations of this approach. Consequently, the MODIS Characterization Support Team (MCST) has developed an alternative approach to monitor the on-orbit RVS change, using a response from a single desert site, with the goal of minimizing the dependence on the site's radiometric stability. This paper updates recent progress in the formulation of the alternative RVS approach. Comprehensive comparisons were also performed with current C6 RVS results for both Terra and Aqua MODIS. Results demonstrate that this alternative method provides an efficient and effective means to track the on-orbit RVS for MODIS RSB.

9218-56, Session 12

Evaluation of Terra and Aqua MODIS thermal emissive band response versus scan angle

Brian N. Wenny, Aisheng Wu, Sigma Space Corp. (United States); Sriharsha Madhavan, Science Systems and Applications, Inc. (United States); Xiaoxiong J. Xiong, NASA Goddard Space Flight Ctr. (United States)

Terra and Aqua MODIS have operated near-continuously for over 14 and 12 years, respectively, and are key instruments for NASA's Earth Observing System. Observations from the 16 thermal emissive bands (TEB), covering wavelengths from 3.5 to 14.4 ?m with a nadir spatial resolution of 1 km are used to regularly generate a variety of atmosphere, ocean and land science products. The TEB detectors are calibrated using scan-by-scan observations of an on-board blackbody (BB). The current response versus scan angle (RVS) of the scan mirror was derived using a spacecraft deep-space pitch maneuver for Terra MODIS and characterized during prelaunch for Aqua MODIS. Earth view (EV) data over the complete range of angles of incidence (AOI) can be used to evaluate the on-orbit performance of the TEB RVS over the mission lifetime. Three approaches for tracking the TEB RVS on-orbit using EV observations are formulated. The first approach uses brightness temperatures (BT) retrieved over the cloud-free ocean to derive the trends at 13 AOI over the mission lifetime. The second approach tracks the dn response (normalized to the BB AOI) across the full swath width for Antarctic granules with the Dome C site at nadir. The third method uses the multiple daily observations of Dome C BT at different AOI and their trend relative to coincident measurements from a ground temperature sensor. The viability of the three approaches is assessed and the long-term stability of the TEB RVS for both MODIS instruments is determined.

9218-57, Session 12

Impact Assessment of MODIS Spectral Bands Locations on the Focal Plane Assemblies to Calibration

Zhipeng Wang, Sigma Space Corp. (United States); Xiaoxiong J. Xiong, NASA Goddard Space Flight Ctr. (United States)

The key on-board calibrators (OBCs) of MODIS include a solar diffuser (SD) for the reflective solar bands calibration and a blackbody (BB) for the thermal emissive bands calibration. MODIS also has a space view (SV) port through which the detectors can view the Moon for various calibration and characterization purposes. As a whisk-broom scanning radiometer, the spectral bands of MODIS are separated on the focal plane assemblies (FPA) in the along-scan direction and aligned into corresponding image frames by delaying the observations from each band accordingly to account for the along-scan motion needed to view the same target point. While this co-registration works well for the "far field" Earth view (EV) target, there exists a band-to-band image frame misalignment in the along-scan direction when the detectors view the "near field" on-board targets, such BB, SD, and the edge of SV. In this paper, we present our analysis of this "near field" misalignment phenomenon. It is shown that the frame misalignment between any band pairs is a linear function of the displacement of their band locations on the FPA and the linear coefficient of the function can be determined from the distance of the object to the scan mirror, with a shorter distance resulting in a larger misalignment. Also discussed in this paper is the calibration impact due to the "near field" misalignment for MODIS and sensors with MODIS-like FPA.

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9219-1, Session 1

The GOSAT / TANSO interferometer after five years on orbit *(Invited Paper)*

Louis M Moreau, James Veilleux, ABB Analytical Measurement (Canada); Hiroshi Suto, Japan Aerospace Exploration Agency (Japan)

GOSAT (Greenhouse Gases Observing Satellite) is a Japanese Earth observation satellite dedicated to the monitoring of total column amount of carbon dioxide and methane over different locations on the planet. The main instrument of GOSAT is the TANSO Fourier Transform Spectrometer (TANSO FTS). NEC-Toshiba Space Systems was the prime integrator of the TANSO FTS. ABB provided the interferometer and its control electronics. The satellite was launched in January 2009. The mission, planned for five years, has exceeded its design life-time.

This paper presents an overview of the interferometer and of its development. Special emphasis is accorded to the life time qualification activities. Analysis of the health of the interferometer on-orbit is presented.

9219-2, Session 1

Space-based carbon monitoring by GOSAT and GOSAT-2: instrumentation and level-1 processing

Hiroshi Suto, Akihiko Kuze, Kei Shiomi, Masakatsu Nakajima, Japan Aerospace Exploration Agency (Japan)

To observe the global column concentration of carbon dioxide (CO2) and methane (CH4) from space, the Greenhouse gases Observing SATellite (GOSAT) was launched on January 23, 2009, and has started the operational observation. Thermal and Near Infrared Sensor for Carbon Observation – Fourier Transform Spectrometer (TANSO-FTS) has been continuously measuring CO2 and CH4 distributions globally, and the retrieved column CO2 and CH4 data have been distributed to the public. During five-years operational periods, which is designed life time for GOSAT, the radiometric, geometric and spectroscopic characterizations were performed for TANSO-FTS and continued these activities to keep the spectral quality in extended mission periods. TANSO-FTS spectra can be retrieved with 2ppm accuracy of XCO2, which is much smaller than 4ppm of the GOSAT mission target. These results have been supporting to well understanding of carbon cycle. To elucidate the carbon cycle more precisely, our experiences on instrumentation have to be summarized and applied in GOSAT-2 instrument, which is next generation of Japanese greenhouse gases observing satellite. GOSAT-2 has the optimized spectral range for XCO2, XCH4 and fluorescence. In addition, it will be carried new functions, which are 2.3um CO detectability, extended sun-glint tracking, and intelligent pointing for clear sky detection. Supporting the cloud detection, improved cloud and aerosol imager are carried and synchronized with FTS operation. The design study of GOSAT-2 instrument has started and will be presented with GOSAT status.

9219-3, Session 1

Onboard infrared signal processing system for asteroid sample return mission HAYABUSA2

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Onboard signal processing system for infrared sensors has been developed for HAYABUSA2 for the exploration of C class near-Earth asteroid 162173 (1999JU3), which is planned to be launched in 2014. An optical navigation camera with telephoto lens (ONC-T), a thermal-infrared imager (TIR), and a near infrared spectrometer (NIRS3) have been developed for the observation of geology, thermo-physical properties, and organic or hydrated materials on the asteroid. ONC-T and TIR are used for those scientific purposes as well as assessment of landing site selection and safe descent operation onto the asteroid surface for sample acquisition. NIRS3 is used to characterize the mineralogy of the asteroid surface by observing the 3-micron band, where the particular diagnostic absorption features due to hydrated minerals appear.

Since the processing cycle of these sensors are independent, data processing, formatting and recording are processed in parallel. In order to provide the functions within the resource limitation of deep space mission, automatic packet routing function is realized in one chip router with SpaceWire standard. Thanks to the SpaceWire upper layer protocol (remote memory access protocol: RMAP), the variable length file system operation function can be delegated to the data recorder from the CPU module of the digital electronics of the sensor system. In consequence the infrared spectrometer data from NIRS3 is recorded in parallel with the infrared image sensors. High speed image compression algorithm is also developed for both lossless and lossy image compression in order to eliminate additional hardware resource while maintaining the JPEG2000 equivalent image quality.

9219-4, Session 1

MERTIS: optical performance of the thermal infrared push-broom imaging spectrometer

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The Mercury Radiometer and Thermal Infrared Spectrometer (MERTIS) onboard the BepiColombo Mercury Planetary Orbiter (MPO) is a state of the art instrument for studies of the surface composition of Mercury. MERTIS is the first spaceborne push-broom spectrometer that allows mapping the Mercury's surface mineralogy in the diagnostic mid-infrared range.

The assessment of the optical performance by optical simulation and testing is presented. Moreover, the method for geometrical calibration of the thermal infrared imaging spectrometer and the fundamentals of this approach are discussed. The demonstrated results underpin the consistency between simulation and real data.

9219-26, Session 1

Advancements in SiPIN hybrid focal plane technology

Sean P. Kilcoyne, Neil R. Malone, Raytheon Co. (United States)

Raytheon has been building silicon p-i-n (Si-PIN) detector arrays for the past thirty years for various remote sensing instruments such as MODIS, EO-1, and Landsat now on orbit. The Hybrid CMOS:Si-PIN technology at Raytheon has matured in the past decade with the addition of a dedicated silicon wafer fab, improvements in wafer to wafer hybrid technologies, and the enhanced digital functionality of RVS custom read out integrated circuits (ROICs). This paper will discuss the recent improvements in Raytheon large format (>5k2) Si-PIN array designs that

offer customizable design space to deliver full digital CMOS functionality, high QE (UV – near IR), high MTF, and radiation hardness.

9219-5, Session 2

CO2 Phase and Amplitude Spectra Measured over 2 km Outdoor Path With a Dual-Comb Spectrometer

Ian Coddington, National Institute of Standards and Technology (United States); Greg B. Rieker, Univ. of Colorado at Boulder (United States); Fabrizio R. Giorgetta, Willaim C. Swann, National Institute of Standards and Technology (United States); Laura C. Sinclair, Chris Comer, National Institute of Science and Technology (United States); Esther Baumann, Nathan R. Newbury, National Institute of Standards and Technology (United States)

We demonstrate simultaneous sensing of CO2, CH4, H2O, and HDO over a 2-km outdoor open air path using dual-frequency-comb absorption spectroscopy (DCS). Our implementation of the novel DCS technique simultaneously offers broad spectral coverage (>8 THz, 267 cm^-1) and fine spectral point spacing (100 MHz, 0.0033 cm^-1) with a coherent eye-safe beam.

We will discuss the development of the DCS spectrometer, which is adapted from [1], and consists of two fiber frequency-comb lasers which create a broad spectrum of perfectly spaced narrow linewidth frequency elements ('comb teeth') near 1.6 microns. In DCS comb frequencies are offset in a Vernier-like fashion so that each pair of comb teeth from the two combs results in a unique rf heterodyne beat frequency on the photodiode. Much like an FTIR, broadband molecular absorption spectra can be recovered on a single photodiode. Unlike FTIR high-resolution (0.0033 cm^-1) DCS instruments require no moving parts, are robust against vibration and are potentially mobile devices. These high-brightness, single-mode sources allow for flexible interrogation geometries, and the narrow comb linewidths provide an essentially negligible instrument lineshape. DCS spectrum can thus resolve neighboring absorption features of different species, and can be compared directly with HITRAN.

As a demonstration a 2 km open air path in Boulder is interrogated. Measurements covering the complete 30013<-00001 absorption band of CO2 and absorption features of CH4, H2O and HDO between 1.6-1.67 microns were performed under a variety of atmospheric conditions.

1. Zolot, et. al., Opt. Lett., 37(4), 638–640, (2012).

9219-7, Session 2

AeroADL: applying the integration of the Suomi-NPP science algorithms with the Algorithm Development Library to the calibration and validation task

Scott Houchin, The Aerospace Corp. (United States)

A common problem for the off-line validation of the calibration algorithms and algorithm coefficients is being able to run science data through the exact same software used for on-line calibration of that data. The JPSS program solved part of this problem by making the Algorithm Development Library (ADL) available, which allows the operational algorithm code to be compiled and run on a desktop Linux workstation using flat file input and output. However, this solved only part of the problem, as the toolkit and methods to initiate the processing of data through the algorithms were geared specifically toward the algorithm developer, not the calibration analyst. In algorithm development mode, a limited number of sets of test data are staged for the algorithm once, and then run through the algorithm over and over as the software is developed and debugged. In calibration analyst mode, we are continually running new data sets through the algorithm, which requires significant effort to stage each of those data sets for the algorithm without additional tools.

AeroADL solves this second problem by providing a set of scripts that wrap the ADL tools, providing both efficient means to stage and process an input data set, to override static calibration coefficient look-up-tables (LUT) with experimental versions of those tables, and to manage a library containing multiple versions of each of the static LUT files in such a way that the correct set of LUTs required for each algorithm are automatically provided to the algorithm without analyst effort. Using AeroADL, the Aerospace Corporation's analyst team has demonstrated the ability to quickly and efficiently perform analysis tasks for both the VIIRS and OMPS sensors with minimal training on the software tools.

9219-8, Session 2

Excellent approach to modeling urban expansion by fuzzy cellular automata: agent-base model

Abdulrazak A. Mohammed, Yousef Khajavigodellou, Salahaddin Univ.-Hawler (Iraq)

Recently the interaction between humans and their environment is the one of important challenges in the world. Land-use/cover change (LUCC) is a complex process that includes actors and factors at different social and spatial levels. The complexity and dynamics of urban systems make the applicable practice of urban modeling very difficult. Fuzzy Cellular Automata) FCA(in Geospatial Information System)GIS(to simulated and predicted urban expansion pattern.Using Cellular Automata in the Land-use/cover change modeling depend on many factors, parameters such as reliability of data and expertise to understand the model will perform. A fuzzy inference guided cellular automata approach. Semantic or linguistic knowledge on Land use change is expressed as fuzzy rules, based on which fuzzy inference is applied to determine the urban development potential for each pixel. In CA, cells are agents and vice versa, but in agent -based modeling agents and cells are totally separate therefore Combined CA-ABM models is an new approach that has been receiving attention by the land use modeling community in recent years, mainly because it offers a way of incorporating the influence of human decision-making on land use in a mechanistic, formal, and spatially explicit way, taking into account social interaction, adaptation, and decision-making at different levels.

9219-9, Session 3

Advanced simulation methods to detect resonant frequency stack up in focal plane design *(Invited Paper)*

Craig Adams, Neil R. Malone, Raymond Torres, Armando Fajardo, John L. Vampola, William Drechsler, Russell Parlato, Christopher Cobb, Max Randolph, Surath Chiourn, Robert Swinehart, Raytheon Co. (United States)

Wire used to connect focal plane electrical connections to external electrical circuitry can be modeled using the length, diameter and loop height to determine the resonant frequency. The design of the adjacent electric board and mounting platform can also be analyzed. The combined resonant frequency analysis can then be used to decouple the different component resonant frequencies to eliminate the potential for metal fatigue in the wires. It is important to note that the nominal maximum stress values that cause metal fatigue can be much less than the ultimate tensile stress limit or the yield stress limit and are degraded further at resonant frequencies.

It is critical that tests be done to qualify designs that are not easily simulated due to material property variation and complex structures. Sine wave vibration testing is a critical component of qualification vibration and provides the highest accuracy in determining the resonant frequencies which can be reduced or uncorrelated improving the structural performance of the focal plane assembly by small changes in design damping or modern space material selection.

Vibration flow down from higher levels of assembly needs consideration for intermediary hardware, which may amplify or attenuate the full up system vibration profile. A simple pass through of vibration requirements may result in over test or missing amplified resonant frequencies that can cause system failure.

Examples are shown of metal wire fatigue such as discoloration and microscopic cracks which are visible at the sub-micron level by the use of a scanning electron microscope.

While it is important to model and test resonant frequencies the Focal plane must also be constrained such that Coefficient of Thermal expansion mismatches are allowed to move and not overstress the FPA.

9219-11, Session 3

Cryogenic filter wheel design for an infrared instrument

Joaquin Azcue, Carlos Villanueva, Antonio Sanchez, Cristina Polo, Manuel Reina, Angel Carretero, Josefina Torres, Gonzalo Ramos, Luis Miguel Gonzalez, Maria Dolores Sabau, INTA Instituto Nacional de Técnica Aeroespacial (Spain); Francisco Najarro, Ctr. de Astrobiología (Spain); Jesus Martin-Pintado, INTA Instituto Nacional de Técnica Aeroespacial (Spain)

In the last two decades, Spain has built up a strong IR community which has successfully contributed to space instruments, reaching Co-PI level in the SPICA mission (Space Infrared Telescope for Cosmology and Astrophysics).

Under the SPICA mission, INTA, focused on the SAFARI instrument requirements but highly adaptable to other missions has designed a cryogenic low dissipation filter wheel with six positions, taking as starting point the past experience of the team with the OSIRIS instrument (ROSETTA mission) filter wheels and adapting the design to work at cryogenic temperatures. One of the main goals of the mechanism is to use as much as possible commercial components and test them at cryogenic temperature.

This paper is focused on the design of the filter wheel, including the material selection for each of the main components of the mechanism, the design of elastic mount for the filter assembly, a positioner device designed to provide positional accuracy and repeatability to the filter, allowing the locking of the position without dissipation. In order to know the position of the wheel on every moment a position sensor based on a Hall sensor was developed. A series of cryogenic tests have been performed in order to validate the material configuration selected, the ball bearing lubrication and the selection of the motor. A stepper motor characterization campaign was performed including heat dissipation measurements.

The result is a six position filter wheel highly adaptable to different configurations and motors using commercial components. The mechanism was successfully tested at INTA facilities at 20K at breadboard level.

9219-12, Session 3

Preliminary study of the Suomi NPP VIIRS detector level spectral response function effects for the long-wave infrared bands M15 and M16

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The Suomi NPP Visible Infrared Imaging Radiometer Suite (VIIRS) Sea Surface Temperature (SST) Environmental Data Record (EDR) team observed an anomalous striping pattern in the SST data. The SST product primarily uses retrievals from VIIRS Bands M15 (10.7 ?m) and M16 (11.8 ?m) radiances. To assess possible causes due to detector level Spectral Response Functions (SRFs), a study was conducted to compare the radiometric response of the detector level and operational band averaged SRFs of VIIRS M15 & M16 under different atmospheric conditions. Typical hyperspectral radiance data was obtained from Infrared Atmospheric Sounding Interferometer (IASI) observations and Radiative Transfer Model (RTM) simulated data [MODTRAN]. Each typical radiance spectra was then integrated with the band average and detector level SRFs to produce pairs of simulated effective radiance that were converted to differences in effective temperature.

Results show differences have a small, but apparent atmospheric dependence for M15 and M16 with differences ranging from near zero to ~0.05 K. Additionally, an odd/even detector pattern was observed in both M15 and M16 channels when each detector was differenced with the band averaged response. Although the observed effect was shown to be small, approximately at the noise level, it may impact the SST product and retrieval algorithms. Future work will focus on characterizing the uncertainties of the detector level measurements and establishing root cause of the odd/even behavior and its impacts on VIIRS data quality.

9219-13, Session 4

Investigating potential correlations between jet engine noise and plume dynamics in the hypertemporal infrared domain

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Jet engine noise can be a hazard and environmental pollutant, affecting personnel working in close proximity to jet engines (such as airline baggage handlers and mechanics). Mitigating the effects of jet engine noise could reduce the potential for hearing loss in runway workers, but engine noise is not yet sufficiently well-characterized that it can easily be mitigated for new engine designs. That is, there exists a very complex relationship between jet engine design parameters, operating conditions, and resultant noise power levels. In this paper, we propose to evaluate the utility of high-speed imaging (also called hypertemporal imaging) in correlating the infrared signatures of jet aircraft engines with acoustic noise from the jet engines.

This paper will focus on a theoretical analysis of jet engine infrared signatures, and will define potentially-detectable characteristics of such signatures in the hypertemporal domain. A systematic test campaign to determine whether such signatures actually exist and can be correlated with acoustic jet engine characteristics will be proposed.

The detection of any hypertemporal signatures in association with acoustic signatures of jet engines will enable the use of a new domain in characterizing jet engine noise. This may in turn enable new methods of predicting or mitigating jet engine noise, which could lead to socioeconomic benefits for airlines and other operators of large numbers of jet engines.

9219-14, Session 4

Detecting small surface vibrations by passive electro-optical illumination

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Toyon Research Corporation and UCSB have performed research to understand the feasibility of using signals received by EOIR sensors to detect small vibrations in surfaces illuminated by sunlight. The vibration models consider buildings with vibrating roofs, as well as

ground vibrations due to buried structures. For the surface buildings, we investigated two approaches. One involved treating the roof as an elastic medium subject to deformation resulting in a PDE whose solution describes the fluctuation in the surface's normal direction vector. The second approach treated the roof as a rigid mass subject to motion in six degrees of freedom, while modeling the dynamics of the building's frame, and tuning the parameters to result in resonant frequencies similar to real buildings. We applied the appropriate physical models of reflected and scattered light to various surfaces, specular (insulator or conductor), rough but still reflective, or diffusely scattering (Lambertian). Matlab code was developed to perform numerical simulations of any system configuration described above and easily add new models. The main engine of the code is a signal calculator and analyzer that sums the total intensity of received light over a "scene" with a variety of surface materials, orientations, polarization (if any), and other parameters. A resulting signal versus time is generated that may be analyzed in order to: 1) optimize sensitivity, or 2) detect the vibration signature of a structure of interest. The results of this study will enable scientists/engineers to optimize signal detection for passive exploitation of scattered light modulated by vibrating surfaces.

9219-15, Session 4

Feasibility considerations for a long-range passive vibrometer

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Advanced imaging techniques can enable long-range characterization of the vibration modes and amplitudes of a passively illuminated surface. The vibration signature arises from modulation of the bidirectional reflection distribution function (BRDF) as the surface normal oscillates with respect to the fixed, directional source. In this paper we propose an instrument design for long-range detection of such vibrations, and consider the instrument design characteristics and environmental factors that limit passive vibrometry performance, including BRDF angle sensitivity, receiver spatial resolution, interference from atmospheric scintillation, and intrinsic detector performance. We identify a sensor architecture that is capable of characterizing surface vibration at low amplitudes from long range, and discuss a novel technology (the Photon-Counting Integrated Circuit, or PCIC), which can provide appropriate performance and fieldability characteristics for use in long-range passive vibrometry.

9219-16, Session 4

A passive optical technique to remotely measure physical properties of a vibrating surface *(Invited Paper)*

Frank O. Clark, Ryan Penney, Spectral Sciences, Inc. (United States); Wellesley E. Pereira, Air Force Research Lab. (United States); Jason Cline, Spectral Sciences, Inc. (United States); John Kielkopf, Univ. of Louisville (United States)

We report an optical technique for determining the physical properties of a vibrating surface. This approach makes use of the detection of light intensity modulation in light scattered from a vibrating surface. The intensity modulation is caused by a changing surface normal. Intensity modulation may be used to produce a vibration image of the observed surface. The vibration frequency at each point on the image is determined by the materials properties of the surface, flexural modulus and mass density. Comparison of the vibration image with, for example, a finite element model, may be used to infer properties of the vibrating surface. The intensity modulation image may also be analyzed to infer spatial damping properties of the material comprising the surface. Damping is a measure of energy dissipation within the material. These physical material properties may be measured remotely.

9219-17, Session PMon

Spectroscopic measurement of ignition parameters in forest fuel

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Fuel Moisture Content (FMC) and leaf biochemical compounds are parameters used to determine forest ignition and can be obtained by different methods, included optical and chemical techniques. Chemical techniques require approximately 20 hours to determine forest fuel chemical compounds and FMC. In contrast, optical techniques need a few minutes to know the FMC. However, this is not able to determine the chemical compounds without previous treatment. PROSPECT is a radiative transfer model technique to describe reflectance and transmittance leaves. Using visual and near infrared (Vis-NIR) spectroscopy, is obtained specific absorption coefficient of leaf extract. This is used as a parameter to invert PROSPECT model and quantify resins, oils and waxes which constitute forest fuel. This research will give the basis for remote Vis-NIR spectroscopy using unmanned aerial vehicles (UAVs) by dynamical ignition parameters acquisition.

9219-18, Session PMon

Supercontinuum spectrum in IR Bessel-Gauss and Gauss pulsed beam filament under anomalous group velocity dispersion in fused silica

Alexandra E. Dokukina, Evgeniya O. Smetanina, Lomonosov Moscow State Univ. (Russian Federation); Victor O. Kompanets, Sergey V. Chekalin, Institute of Spectroscopy (Russian Federation); Valeriy P. Kandidov, Lomonosov Moscow State Univ. (Russian Federation)

The filament supercontinuum (SC) was investigated experimentally and numerically in number of focusing schemes including axicon and lens in fused silica under anomalous group velocity dispersion (GVD).We used femtosecond (50 fs) pulses with Bessel-Gauss spatial profile and with central wavelength 1.8-microns what corresponds to anomalous GVD in fused silica. The relation between pulse spatio-temporal dynamics and SC generation was found.

The sequence of light bullets is formed under anomalous GVD [1]. Visible part of SC is emitted when each light bullet appears. Energy of the visible SC linearly depends on the number of the light bullets in the filament.

Bessel-Gauss pulse spatial profile allows using higher pulse energies in one-filament regime then the Gauss pulse profile. So, a sequence of light bullets is longer and SC generation is more efficient under axicon focusing then under lens focusing.

1. Smetanina E.O., Kompanets V.O., Dormidonov A.E., Chekalin S.V., Kandidov V.P. Laser Physics Letters, 10, 105401 (2013).

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9219-19, Session PMon

Stand-off and up-close Raman detection of nitrates buried in sand and soils

Carlton W. Farley III, Sandra Sadate, Aschalew Kassu, Alabama

A&M Univ. (United States); Belther Monono, Alabama A&M University (United States); William Witt, Auburn University (United States); Anup Sharma, Alabama A&M Univ. (United States)

Raman measurements, using a 785nm laser, are taken of Ammonium Nitrate and Sodium Nitrate buried in sand. Nitrate is kept in clear plastic containers and buried underneath sand at several different depths. Raman measurements are then taken at distances of 7mm, 1m, and 5m, with the sand being completely dry as well as completely wet. Similar measurements are taken of white plastic buried in sand. A different set of experiments was conducted with Nitrate buried in different depths of sand in a glass container, where no Raman signal was seen in dry sand. Water was then added at the edge of the container and allowed to migrate to the bottom. Raman measurements are then taken at a distance of 7mm over time to detect Nitrates brought to the surface by water as it wicks to the surface.

9219-20, Session PMon

Stand-off Raman detection of hidden explosives

Sandra Sadate, Carlton W. Farley III, Aschalew Kassu, Anup Sharma, Alabama A&M Univ. (United States)

Using Raman spectroscopy, we have detected ammonium nitrate hidden behind different materials with different colors. Ammonium nitrate is a substance relevant in the making of improvised explosive devices. Because of the need for real time detection and fast result, these measurements were taken in 10 seconds or less. The standoff Raman system used in this work consists of a 2-inch refracting telescope for collecting the scattered Raman light and a 785nm laser operating at 400mW coupled with a small portable spectrometer.

9219-21, Session PMon

3D shape measurement with binary phase-shifted technique and digital filters

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Shape measurements by sinusoidal phase-shifting methods require high-quality sinusoidal fringes. Furthermore, most of the video projectors have a nonlinear response, which makes difficult to generate high quality phase without the calibration and correction of the nonlinearity. To overcome the limitations of the conventional digital fringe projection techniques, we proposed a method that involves the projection of digital binary patterns generated by the pulse-width modulation (PWM). We will demonstrate that applying regularization methods, in particular, low pass filters; one can obtain a high-quality sinusoidal pattern. In order to use phase-shifting methods, at least two binary patterns can be encoded in the color components of a single color image, which allows a reliable 3-D profiling surface reconstruction at large time-rates. Validation experiments using a commercial video projector are presented.

9219-22, Session PMon

Gray coded trapezoidal fringes for 3D surface-shape measurement

Jorge L. Flores-Nuñez, Oscar G. Pérez, Guillermo García-Torales, Univ. de Guadalajara (Mexico); J. Antonio Muñoz-G, Univ de Guadalajara (Mexico); Horacio Soto, Ctr. de Investigación Científica y de Educación Superior de Ensenada B.C. (Mexico); Sandra E. Balderas-Mata, Univ. de Guadalajara (Mexico)

We propose a trapezoidal phase-shifting method, for 3-D shape measurements. Shape measurements by trapezoidal phase-shifting methods require high-quality trapezoidal patterns. Furthermore, most of the video projectors have a nonlinear response, which makes difficult to generate a high quality patterns without the calibration and correction of the nonlinearity. To overcome the limitations, we propose a method for synthesizing trapezoidal intensity fringes as a way to solve the problems caused by the projector/camera gamma nonlinearity. The fringe generation technique consists of projecting and acquiring a temporal sequence of strictly binary color patterns (or Gray code), its average (adequately weighted) leads to trapezoidal fringe patterns with the required number of bits, which allows a reliable three-dimensional profile reconstruction using phase-shifting methods. Validation experiments are presented.

9219-23, Session PMon

Evaluate the effective of annular aperture on the OTF for fractal optical modulator

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The fractal optical modulator is the optical modulator design by using the fractal function. As well known there is an effect of aperture's shape on the OTF signal for optical modulator. In present paper an aberration-free single annular aperture has used and the MTF characteristics responses investigate for fractal optical modulator of IR-Seeker .The annular aperture provide several frequency transmission bands within the region up to cut-off frequency. The result compared with the spatial frequency for circular shape of fractal optical modulator aperture.

9219-25, Session PMon

A near infrared-based downhole water-cut meter using neural network technique

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With the continuous increase of oil production from relatively aging wells, today's oil fields are continuously depleting and are mostly subject to second and third recovery methods using CO2 and/or water injection. This led oil wells to be water saturated within which very high water cut is usually attributed to the extracted crude oil. Real-time and downhole measurement of crude oil with a water cut exceeding 90% remains a challenging task for traditional water-cut sensing devices. Thus lots of research efforts have been conducted for designing new down?hole water cut meters. Gamma-based sensors [3, 4] are widely used for measuring fluid concentration. These devices use a nuclear source to expose the target region to a high energy beam of gamma ray and can provide very accurate water-cut for a range exceeding 90 % water-cut. However, they are hazardous and not intrinsically safe since they require high amount of energy during the emission. Coriolis meters measures the fluid density (and hence its water-cut) with high accuracy (i.e. can be less than 0.2% relative error) by tracking the natural frequency of the vibrating pipe carrying the fluid. However, these devices require vibration sources making them mechanically complex and relatively difficult to be deployed downhole. In addition, their moving parts may easily lead to the corrosion of the sensor if the target fluid contains conductive fluid (e.g. water). Electrical sensors such as capacitance and conductance sensors feature fast response time and have been extensively used in oil fields to determine the oil-water fraction [5, 8, 7]. However, they can't cover the range of 40 to 60% water-cut, in addition to water cut exceeding 90%. In addition, these sensors fail to handle some types of flow regimes (e.g. stratified flow regime) [1]. Optical sensors using visible light [8] have demonstrated high accuracy in addition of being neither intrusive nor invasive.

However, they can't deal with build-up particles caused by crude oil and also they can cope with nontransparent crude oil. From the algorithmic point of view, many devices rely on some analytical models extracted from fluid mechanics theory. However, this approach is not yet proved

to be practical since it relies usually on simplified equations requiring a prior knowledge of various properties of the pipes in the flow loop (e.g. fluid density and pipeline geometry). In this paper, a new NIR-based device for down whole and high water-cut measurement is presented. The device consists of an array of NIR optical fiber emitters and receivers which surround the target object. Lenses are attached to each individual emitter/receiver pair in order to expand the Field of view (FOV). A single hidden-layer feed forward artificial neural network algorithm was used to determine the value of the water-cut cut by considering ten representative wavelengths which where extracted using the principal component analysis (PCA) wavelengths. This led to achieve an accurate water-cut measurement with less than 0.5 % error.

9219-32, Session PMon

Latchable mechanical deformable mirror for improvement of performance of space-borne telescopes

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Wavefront correction (WFC) of an astronomical infrared telescope is important technique to improve image quality. To realize WFC, deformable mirrors (DMs) based on technology of MEMS or piezo-electric material are conventionally used. Such DMs have quick response, so they are suitable to correct atmospheric turbulence. On the other hand, it is not easy to make such DMs latchable, so such DMs needs to be driven successfully, continually, and very stably for long time. Indeed, this point is considered as an important risk of space telescope missions. Therefore, we are developing a new mechanically operated DM which is latchable, i.e., driving force is necessary only when the mirror surface figure is changed. The purpose of the mechanical DM is to compensate surface figure error of space telescopes which are much more stable than wavefront error caused by air turbulence. Recently we succeeded to develop our first leachable compact DM which is made from a monolithic metal cube. One surface of it is polished to be mirror surface of 25mmx25mm. Wire-electric machining cut out the body of the cube and construct soft (flexure) structures in the body. Then 5x5 deformable elements are realized. The mirror surface is deformed by screw-driver at the backside. We measured its successful deformation with an interferometer at ambient temperature. The latchable DM is complementary with conventional DMs. Our mechanically operated DM is also designed to survive at 5K which is temperature of advanced space infrared telescopes.

9220-27, Session PMon

Land salinization classification method using Landsat TM images in Western Jilin Province of China

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In the study of land salinization monitoring, researchers are most concerned about data variation, such as distribution, area and the degree of salinization. Traditional testing methods need to manually extract data from field, which costs amount of time, manpower and money. As a result, we cannot get data in time. In recent years, with the development of remote sensing technology, remote sensing data with multi-band and multi-temporal is used to extract and analyze the information of saline-alkali soil using manual interpretation.

At present, most researches focus on visible spectrum of remote sensing data, which are limited by imaging conditions of optical sensors. Therefore, some errors inevitably exist in the monitoring results of land salinization. Based on spectral and microwave characteristics of ground objects, the west of Jilin province of China is selected as research area. Landsat TM images combined with MWRI data are used to do some types of processing, including data preprocessing and classification, which are further compared with the sample data extracted in the field over the same test period. The relationship between the information obtained from remote sensing data and the different types of saline-alkali land is built in this paper. The experimental results demonstrate that the propose method is more effective in land salinization monitoring, which can provide more accurate classification, area statistics and dynamic monitoring information.

9220-28, Session PMon

Inkjet-printed cytochrome c protein for long wavelength infrared sensing

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Infrared thermal imager is an increasingly important device in the military use and commercial operation. The infrared thermal imager can be used in thermal sensing cameras, industrial monitoring, automotive applications, firefighting, medical care, nighttime surveillance etc. The microbolometer is composed of the infrared optical lens system, focal plane array (FPA), readout integrated circuit (ROIC), and imaging display. Because of the importance of focal plane array (FPA), our research focuses on it. Microbolometer generates the signals with the resistance changed by temperature difference. The efficiency of focal plane array is mainly determined by the sensitivity of the sensor material and the thermal insulation of the supporting structure. Cytochrome c is the promoting sensing material inkjet printed on the suspending structure because of its high TCR value.

The cytochrome c (protein) thin film has been reported high temperature coefficient of resistance (TCR), which is related to the performance of microbolometer directly. Hence the superior TCR value will increase the performance of microbolometer. Cytochrome c solutions were ink-jetted onto the aluminum structure by using the inkjet printer.

In order to reduce the heat loss, we have to lift off the structure to separate the microbolometer from the substrate. Therefore, we should design a desk-shaped structure. We create a slot in the middle on the desk top that the protein will be drop on. Besides, the desk body is hollowed to reduce the heat loss and the legs on the either side are left to support the desk top. With this structure, we can further measure the responsivity and detectivity.

9220-29, Session PMon

Analysis of local charge-carrier diffusion length values in the photosensing film of photovoltaic HgCdTe FPA photodetectors

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The diffusion length of photogenerated charge carriers in absorber layer is an important parameter defining the majority of performance characteristics of hybrid photovoltaic HgCdTe FPA photodetectors, including their photoelectrical crosstalk, the collection area of excess carriers, etc. This length can be judged from spot-scan measurements performed at different levels of photocurrents jph being extracted by ROIC out of the HgCdTe film. In the limit jph?0, the bulk charge-carrier diffusion length in the HgCdTe material ld is obtained, which can also be interpreted as the effective diffusion length ld eff (with allowance for current suction) on part of the FPA surface free of diodes. Based on a comparison of results of spot-scan measurements performed at jph≠0 with simulated data, we can also evaluate the value of ld eff on part of the FPA surface occupied by photodiodes. The data thus obtained provide an extensive basis for analyzing the diffusion process of excess charge carriers in the photosensitive film of IR FPA detectors within a simple 2D diffusion model. On performing such an analysis, we found that the obtained values of ld in the HgCdTe films of examined MWIR and LWIR FPA photodetectors (19.5 to 24 ?m) agreed fairly well with relevant literature data for Hg vacancy-doped HgCdTe. Simultaneously, the estimated values of ld eff in the region under photodiodes proved to be consistent with an a priori estimate of this length based on consideration of the typical shape of cross-film distributions of the excess density of charge carriers in that region.

9220-30, Session PMon

Detection of adulteration in onion powder by using FT-NIR and FT-IR spectroscopy

Byoungkwan Cho, Sangdae Lee, Lohumi Santosh, Hoonsoo Lee, Chungnam National Univ. (Korea, Republic of)

Spices are increasingly subjected to adulteration, which highly affects spice quality as well as consumer's satisfaction. By considering the issue, this study was conducted to detect adulteration in onion powder. Fourier transform near infrared (FT-NIR) and Fourier transform infrared (FT-IR) spectroscopic methods were used to detect the presence of added starch in onion powder. The reflectance spectra from 120 samples of various adulteration concentrations were collected. The collected samples spectra of both FT-NIR and FT-IR spectroscopy were preprocessed with various preprocessing methods and divided into calibration and prediction set. Finally a multivariate classification model of partial least square discrimination analysis (PLS-DA) was executed on pretreated spectra to quantitatively predict the presence of starch in onion powder. The PLS-DA model produced classification rate for the FT-NIR data was 98.9% for calibration and 93.3% for prediction set, and for the FT-IR data was 92.2% and 80% for calibration and validation sets respectively. The result shows better classification of FT-NIR data when compared to FT-IR data. The mean of raw spectra shows some important peaks associate with starch that intensity is proportional to the adulteration concentration. In addition beta coefficient of PLS-DA model revealed some absorption peaks that are related to starch. These spectroscopic methods can also be applied to detect adulteration in other spices as they allow non-destructive and rapid analysis with an assay time of 1-2 min.

9220-1, Session 1

Hall Effect and negative energy gap in HgTe/CdTe superlattice with thick quantum wells

Abdelhakim Nafidi, Hassan Chaib, Aomar Idbaha, Driss Barkissy, Abderrazak Boutramine, Univ. Ibn Zohr (Morocco)

We report here manifestation of negative energy gap, resonant state and transition semiconductor-semimetal inducted by temperature in transport properties and bands structure in HgTe (d1=40 nm)/CdTe (d2=15 nm) superlattice (SL) grown by MBE. Calculations of the spectres of energy E(d2), E(kz) and E(kp), respectively, in the direction of growth and in plane of the superlattice; were performed in the envelope function formalism. The energy E(d2, ?, 77 K), shown that when d2 increase the gap Eg decrease to zero at the transition semiconductor to semimetal (SC-SM) conductivity behaviour (at d2=11,5 nm) and become negative accusing a semi metallic conduction. Whereas the band gap Eg(T) increases from -4.1 meV at 4.2 K, to 0 at 148 K with a transition (SM-SC) and to 6.06 meV at 300K. At 4.2 K, the sample exhibits n type conductivity with a Hall mobility of 1600 cm2/Vs, increase with the temperature and reach a maximum of 8000 cm2/Vs at T=148 K of the transition (SM-SC) and decreases in the intrinsic regime. The weak-field Hall coefficient present a small maximum at about 31 K attributed to the presence of an acceptor resonant state. In intrinsic regime, RH T3/2 indicates a gap Eg=5,3meV in agreement with calculated Eg(?, 300 K)= E1-HH1 =6 meV.. The formalism used here predicts that this sample is a narrow gap semimetallic, two-dimensional and far-infrared detector. Ref: M. Braigue, A. Nafidi, A. Idbaha, et al, Journal of Low Temperature Physics, Volume 171, Issue 5-6, (2013), 808-817.

9220-2, Session 1

Interface and facet control during Czochralski growth of (111) InSb crystals for cost reduction and yield improvement of IR focal plane array substrates

Nathan W. Gray, Victor Perez-Rubio, Joseph Bolke, William B. Alexander, Sylarus Technologies (United States)

Focal plane arrays (FPAs) made on InSb wafers are the key cost-driving component in IR imaging systems. The electronic and crystallographic properties of the wafer directly determine the imaging device performance.

The "facet effect" is a phenomenon in InSb bulk crystal growth where the segregation coefficient of dopant impurities changes drastically across the melt/solid interface of a growing crystal. This results in severely non-uniform electronic properties across wafers made from crystals grown on the (111) axis. FPA devices made on these wafers suffer costly yield hits due to inconsistent device response and performance. Our legacy InSb crystal growth process used a common method to avoid these problems by growing off-axis crystals, requiring an expensive custom manufacturing process designed around recovering wafers in the correct orientation.

It has been shown by researchers in the 1960s that control of the facet effect can produce uniform small diameter crystals. We have successfully developed a process which controls the facet effect even when growing large diameter crystals from which 4, 5, and 6" wafers can be manufactured. The process change resulted in an increase in wafers yielded per crystal by several times, all with high crystal quality and uniform electronic properties. Since the crystals are grown on the (111) axis, manufacturing (111) oriented wafers is straightforward with standard semiconductor processing equipment used by high-volume silicon wafer makers. These benefits result in sizeable manufacturing cost savings which can be passed on to the customers.

9220-3, Session 1

Fabrication of resonator-quantum well infrared photodetector test devices

Jason Sun, Kwong-Kit Choi, Kimberley A. Olver, U.S. Army Research Lab. (United States)

We have established a three-dimensional finite element electromagnetic (EM) model to calculate QE quantitatively. This theoretical tool allows us to design new optical coupling structures to achieve a larger QE. One of these detector structures is known as the resonator-QWIP or R-QWIP. To achieve the expected performance, the detector geometry must be produced in precise specification and the substrate of the detector has to be removed to prevent the escape of unabsorbed light from the detector. In particular, the height of the diffractive elements and the thickness of the active resonator must be uniformly and accurately realized to within 0.05 ?m accuracy. To achieve this specification, two optimized selective and non-selective ICP etching processes were developed and applied to fabricate 40 ? 40 small format test detector arrays. Our selective ICP etching process has an optimized BCl3/SF6/Ar composition and shows a nearly infinite etching selectivity for the GaAs over the AlxGa1-xAs etch-stop layer. We used it to create the diffractive elements in the R-QWIP structures and remove the substrate completely. Meanwhile, the non-selective ICP etching process was used to perform straight sidewall, damage-free ground contact etching and pixel mesa etching. The test results of the R-QWIPs agree with EM designs satisfyingly. The highest QE observed is 70.8% with thin detector material and without an anti-reflection coating. The QE could be even higher with further material and structural optimizations. The fabrication of large format 1K ? 1K focal plane arrays with different pixel sizes (25 and 18 μm) is underway.

9220-4, Session 1

Embedded plasmonic-enhanced quantum well infrared photodetector

Robert L. Brown, Alireza Bonakdar, Sung Jun Jang, Northwestern Univ. (United States); Omer G. Memis, Intel Corp. (United States); Hooman Mohseni, Northwestern Univ. (United States)

Quantum Well Infrared Photodetector (QWIP) is an attractive candidate for long-wave infrared detection due to the low-cost and well-developed growth and fabrication technology for III-V semiconductors compared to long-wave infrared interband detectors. However, two major issues with QWIP are its low quantum efficiency and its polarization sensitivity. Plasmonic structures have been demonstrated to solve these issues by coupling and enhancing incident IR signal at the active region. However, these solutions have yet to be made into a device suitable for a Focal Plane Array (FPA) due to either a risk of damaging the plasmonic structure or significant distance of the structure from the detector itself. Here we propose a detector with an embedded plasmonic structure surrounding the detector that is protected.

Our detector uses a periodic hexagonal array of small pillars of QWIP medium surrounded by a plasmonic metal and planarized and contacted from the top making one "super pixel". The plasmonic array is not only protected from bump-bonding, but is in very close proximity to our detecting medium. Also, because we reduce the QWIP to pillars that fill in the plasmonic holes, we eliminate a lot of the "dead space" that contributes to dark current but not to absorption or photocurrent.

9220-5, Session 2

Study of real-time image denoising and hole-filling for micro-cantilever IR FPA imaging system

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Xiaomei Yu, Peking University (China); Mei Hui, Hong Wu, Beijing Institute of Technology (China)

This paper proposes and experimentally demonstrates a new denoising and hole-filling algorithm through discrete points removal and improved bilinear interpolation based on the bi-material cantilever FPA infrared imaging system. In practice, because of the limitation of FPA manufacturing process and optical readout system, the quality of obtained images is always not satisfying. A lot of noise and holes appear in the images, which restrict the application of the infrared imaging system. After analyzing the causes of noise and holes, an algorithm is presented to improve the quality of infrared images. Firstly, the statistic characteristics such as probability curve and gray mean ratio of images with noise are analyzed in great detail. Then, IR images are denoisd by the method of discrete points removal. Second, the holes are filled by improved bilinear interpolation. In this step, the reference points are found through partial derivative method instead of using the edge points of the holes simply. It can detect the real points effectively and enable the holes much closer to the true values. Finally, the algorithm is applied to real-time infrared imaging system successfully. Experimental results show that the IR images can be denoised effectively and the SNRs are improved substantially. Meanwhile, the filling ratios of target holes reach as high as 100% and the visual quality is achieved well. It proves that the algorithm has the advantages of high speed, great precision and easy implement. It is a highly efficient real-time image processing algorithm for bi-material micro-cantilever FPA infrared imaging system.

9220-6, Session 2

Hyperspectral modeling of an infrared Focal Plane Array

Salima Mouzali, Sidonie Lefebvre, Sylvain Rommeluère, Yann Ferrec, Jérôme Primot, ONERA (France)

Infrared Focal Plane Arrays (FPA) are increasingly used to measure multi- or hyperspectral images. Therefore, it is crucial to control their spectral response. The purpose of this paper is to propose a modeling approach, which takes into account the spectral response of the pixels in the design of spectro-imagers or spectrometers. The promising results are illustrated on Microspoc (MICRO SPectrometer On Chip), a concept of miniaturized infrared Fourier transform spectrometer, integrated on a classical Mercury-Cadmium-Telluride FPA, and cooled by a cryostat. The interferometer cavity creates a bi-dimensional interferogram inside the active layer of the FPA. Not only it is a compact instrument, but this snapshot spectrometer also provides very fast acquisition of spectral signatures (up to few hundreds of Hz), with about 155 bands between 1.5 µm and 5 µm. However, a mere Fourier transform inversion of interferograms is not sufficient to obtain good quality spectra, owing to unwanted interference inside the active layer of the photodetector. Thus, the modeling approach was investigated for a more robust inversion. Two models are presented, taking into account various optogeometrical properties of the detector, such as disparities of the pixels cut-off wavelengths. The physical model is based on a multilayer formalism, describing each optical layer by a characteristic matrix, which depends on the thickness and the refraction index of the layer. It gives a valuable understanding of the phenomenons inside the structure. The analytical model considers only the major waves interfering, and is simpler to use for interferograms inversion.

9220-7, Session 2

Surface resistivity and dielectric constant temperature dependence measures of pure and multiwall carbon nanotubes (MWCNT) and silver nano-particle doped polyvinylidene difluoride (PVDF)- and polyvinyl alcohol (PVA) films

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The detection of infrared radiation (IR) with pure and doped Polyvinylidene difluoride (PVDF film) has been well documented using the mechanism of pyroelectricity. The investigation of the surface and volume resistivities of such films, to this point, has received far less consideration. In this research, the authors report surface resistivity temperature dependence measures of pure and multiwall carbon nanotubes (MWCNT) doped PVDF films. Consistently, in the temperature range from 28 0C to 55 0C, with a humidity control environment, the authors find the surface resistivity to decrease as the temperature increases. The research was conducted with the combined instrumentation, of the Keithley Model 6517 Electrometer and Keithley Model 8009 resistivity test fixture with both commercial and in-house produced solution cast PVDF films. With the objective to quantify the suitability of PVDF films as IR detector materials, when using the surface resistivity mechanism, instead of pyroelectricity, the surface resistivity surface effect detectivity D* and other relevant quality factor measures are reported when considering bolometry. Finally, for comparative and suitability purposes, the authors also report the frequency and temperature dependence dielectric constant measures of pure- and MWCNT:PVDF films in frequencies up to 10 MHZ, using Agilent's model 4294 Impedance Analyzer coupled to its 16451B test fixture.

9220-8, Session 3

The influence of sunlight irradiation on the characteristics of InGaAs detectors

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InGaAs ternary compound is suitable for detector applications in the shortwave infrared (SWIR) band. Due to the advantages of good stability, low cooling requirements and high detectivity, InGaAs detectors have been applied widely in the space remote sensing area. However, InGaAs detectors would be affected by strong sunlight direct irradiation in space application. In this paper, a mesa-type InGaAs detector with large sensitive area of diameter 5mm was designed based on InP/In0.53Ga0.47As/InP epitaxial material, which is lattice-matched to InP substrate. The InGaAs detectors were fabricated by ICP etching, and packaged in a Kovar shell. The relative spectral response is in the range of 0.9?m to 1.7?m. The mechanism of the sunlight direct irradiation on InGaAs detector performance was studied. The sunlight were focalized by lens and irradiated directly on the detector. A piece of epitaxial material was investigated at the same time which was cleaved from a 2 inch wafer, same to the detector material. The real time testing was taken out to observe the output signal of the detector. After the irradiation experiment, the I-V curves and the relative response were tested immediately. The dark current of the detector increased temporarily, but come back to the original level after 24 hours. The response spectrum was nearly not affected. The XRD testing of the epitaxial material sample was carried out before and after sunlight direct irradiation. The sunlight irradiation causes thermal stress degradation. The thermal electrons were produced by the absorption of a great deal of visible light, leading to local enhancement of temperature and the lattice degeneration of the material.

9220-9, Session 3

Study on 512x128 pixel InGaAs near infrared focal plane arrays

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It is well known that In0.53Ga0.47As epitaxial material is lattice-matched to InP substrate corresponding to the wavelength from 0.9?m to 1.7?m, which results to high quality material and good device characteristics at room temperature. In order to develop the near infrared multi-spectral imaging, 512x128 pixel InGaAs Near Infrared Focal Plane Arrays were studied. The n-InP/i-InGaAs/n-InP double herteostructure epitaxial material was grown by MBE. The 512x128 back-illuminated planar InGaAs detector arrays were fabricated, including the improvement of passivation film, grooving the diffusion masking layer, the P type electrode layer, In bump condition and so on. The photo-sensitive area has the diffusion area of 23x23μm2 and pixel pitch of 30x30μm2. The 512x128 detector arrays were individually hybridized on readout integrated circuit(ROIC) by Indium bump based on flip-chip process to make focal plane arrays(FPAs). The ROIC is based on a capacitive trans-impedance amplifier with correlated double sampling and integrated while readout (IWR) model with high readout velocity of every pixel resulting in low readout noise and high frame frequency. The average peak detectivity and the response non-uniformity of the FPAs are 1.63?1012 cmHz1/2/W and 5.9%, respectively. The power dissipation and frame frequency of the FPAs are about 180mW and 400Hz, respectively.

9220-10, Session 3

Resonant scanning mechanism

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Ball Aerospace & Technologies Corp. (BATC) has developed a Resonant Scanning Mechanism (RSM) capable of combining a 250 Hz resonant scan about one axis with a 2 Hz triangle scan about the orthogonal axis. The RSM enables a rapid, high density scan over a significant field of regard while minimizing size, weight and power requirements. The azimuth scan axis is bearing mounted allowing for 30° of mechanical travel, while the resonant elevation axis is flexure and spring mounted with 5° of mechanical travel. Pointing knowledge error during quiescent static pointing at room temperature across the full range is better than 100 urad RMS per axis. The compact design of the RSM, roughly the size of a soda can, makes it an ideal mechanism for use on low altitude aircraft and unmanned aerial vehicles. Unique aspects of the opto-mechanical design include i) resonant springs which allow for a high frequency scan axis with low power consumption; and ii) an independent lower frequency scan axis allowing for a wide field of regard. The pointing control system operates each axis independently and employs i) a position loop for the azimuth axis; and ii) a unique combination of parallel frequency and amplitude control loops for the elevation axis. All control and pointing algorithms are hosted on a 200 MHz microcontroller with 516 KB of RAM on a compact 3”x4” digital controller, also of BATC design.

9220-11, Session 3

MWIR InAsSb FPA data and analysis

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InAsSb material with a cutoff wavelength in the 5 um range has been grown on GaAs substrates. The 1024 x 1024 on 18 um pitch MWIR InAsSb detector arrays were fabricated and hybridized to ROICs to permit measurement of the electrical and optical properties at 150 K. The ROIC operates at 25 Hz frame rate and has a well capacity of 20.7 M electrons. QE at 150 K for a 1024 x 1024 detector array was 67%. The median D* at 150 K under a flux of 1.07 x 10^15 ph/(cm^2/s) was 1.2 x 1011 cm (Hz^1/2)/W. The NEdT was 44 mK and imagery was obtained at 150 K using an f/2.3 MWIR lens.

9220-12, Session 4

Human suspicious activity recognition in thermal infrared video

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Detecting suspicious behaviors is important for surveillance and monitoring. In this paper, we investigate suspicious activity detection in thermal infrared imagery, where human motion can be easily detected from the background regardless of the lighting conditions and colors of the human clothing and surfaces. We use locally adaptive regression kernels (LARK) as patch descriptors, which capture the underlying local structure of the data exceedingly well, even in the presence of significant distortions. Patch descriptors are generated for each query patch and for each database patch. A statistical approach is used to match the query activity with the database to make decision of suspicious activity. Human activities in different condition such as, walking, running, walking with a gun, running with a gun, and carrying bag-pack data acquired-using thermal infrared in different terrains are used for training and performance evaluation of the algorithm. The algorithm has compared with the 3D SIFT and STIP descriptor based code book approaches. Experimental results show that the proposed approach achieves good performance in suspicious activity recognition.

9220-13, Session 4

Analysis of total oil content and fatty acid composition by NIR reflectance spectroscopy in edible nuts

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Near Infrared (NIR) Reflectance spectroscopy has established itself as an important tool in quantifying water and oil present in various food materials. It is rapid and nondestructive, easier to use, and does not require processing the samples with corrosive chemicals that would render them non-edible. Earlier, the samples had to be ground into powder form before making any measurements. With the development of new soft ware packages, NIR techniques could now be used in the analysis of intact grain and nuts. While most of the commercial instruments presently available work well with small grain size materials such as wheat and corn, the method present here is suitable for large kernel size products such as shelled or in-shell peanuts. Absorbance spectra were collected from 400 nm to 2500 nm using a NIR instrument. Average values of total oil contents (TOC) of peanut samples were determined by standard extraction methods, and fatty acids were determined using gas chromatography. Partial least square (PLS) analysis was performed on the calibration set of absorption spectra, and models were developed for prediction of total oil and fatty acids. The best model was selected based on the coefficient of determination (R2), Standard error of prediction (SEP) and residual percent deviation (RPD) values. Peanut samples analyzed showed RPD values greater than 5.0 for both absorbance and reflectance models and thus could be used for quality control and analysis. Ability to rapidly and nondestructively measure the TOC, and analyze the fatty acid composition, will be immensely useful in peanut varietal improvement as well as in the grading process of grain and nuts.

9220-14, Session 4

Temperature-tuned erbium-doped fiber ring laser with Mach-Zehnder interferometer based on two quasi-abrupt tapered fiber sections

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We present a wavelength tuning of an Erbium-Doped Fiber Ring Laser (EDFRL) based in a Mach-Zehnder fiber interferometer (MZFI) that consists on tapers fabricated on commercial SMF28 from Corning as an intracavity filter, which spectral interference pattern of the MZFI is modified by external refractive index changes that alter its transmission characteristics of the light. In this work, the fiber device is immersed in a glycerol solution with higher dispersion its refractive index with temperature. Since the temperature sensitiveness of the glycerol is much higher than that of the fiber in a temperature range from 25-110 °C, therefore, the spectral changes are mainly due to the dispersion of glycerol refractive index with heat increase. Also, when this device is inserted into the EDFRL cavity, the gain spectrum of the EDF is modified accordingly and these changes that can be controlled in an electrical heater, allows the tuning of the laser wavelength determined by the interference fringes. A wavelength shift as high as 180 pm/°C and tunable range of 12 nm are obtained. The side mode suppression ratio (SMSR) of the fiber laser reaches 30 dB and decreases to 25 dB depending on the position of the notch filtering, one more aspect of this proposal is that the insertion losses of the filter are below 0.3 dB and the measured wavelength shift has a quasi-linear dependence as a function of temperature in the 80-110 °C. This method is very simple, portable and inexpensive over traditional methods to tune a fiber laser.

9220-15, Session 4

Development of blood vessel search system by using NIR light for blood sampling

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We developed an accurate three-dimensional blood vessel search (3D BVS) system by using NIR light for the automatic blood sampling. In the previous study, the 3D BVS system, which used near-infrared (NIR) light imaging and the stereo method to detect blood vessel accurately in three dimensions. However, as NIR light is not able to transmit the human arm, this system is not available for the subcutaneous blood vessel detection. In this study, we developed a new BVS system by using the reflecting NIR light for the blood sampling. A light propagation simulation was adopted to investigate the fading of the blood vessel image and determined the NIR light irradiation angle and the power. In this simulation, the optical properties, such as the refractive index scattering and absorption, was set similar with human ones. Next, we fabricated a multilayer phantom, which has the similar structure and optical properties with the human skin to examine the accuracy of our BVS system. Since the optical property of human skin has uncertainty, therefore, we fabricated the phantoms, which have exact optical properties, such as the scattering and absorption coefficients, for BVS accuracy examination. Further, the optical properties of our phantom are adjustable to imitate the different color of skin. We evaluated the accuracy of our BVS system by using these phantoms, and established the estimation algorithm to detect the blood vessel accurately. Finally, we confirm the availability of our BVS for the blood sampling system.

9220-32, Session 4

High reflected cubic cavity as long path absorption cell for infrared gas sensing

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One direct and efficient method to improve the sensitivity of infrared gas sensors is to increase the optical path length of gas cells according to Beer-Lambert Law. In this paper, cubic shaped cavities with high reflected inner coating as novel long path absorption cells for infrared gas sensing were developed. The effective optical path length (EOPL) for a single cubic cavity and tandem cubic cavities were investigated based on Tunable Diode Laser Absorption Spectroscopy (TDLAS) measuring oxygen P11 line at 763 nm. The law of EOPL of a diffuse cubic cavity in relation with the reflectivity of the coating, the port fraction and side length of the cavity was obtained. Experimental results manifested an increase of EOPL for tandem diffuse cubic cavities as the decrease of port fraction of the connecting aperture f', and the EOPL equaled to the sum of that of two single cubic cavities at f'<0.01. The EOPL spectra at infrared wavelength range for different inner coatings including high diffuse coatings and high reflected metallic thin film coatings were deduced.

9220-16, Session 5

Approaching high temperature photon counting with electron-injection detectors

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Practical systems for optical quantum information technology require efficient, low noise single-photon detector elements operating in the short wave infrared (SWIR) range of the electromagnetic spectrum. The strongest candidates for SWIR photon number resolving (PNR) are the transition-edge superconducting (TES) sensors and semiconductor APDs. Both technologies, however, suffer from inherent properties that limit their applications.

Our group previously demonstrated a novel telecom wavelength linear-mode detector based on a type-II band alignment called the "electron-injection detector". The detector operates at low bias voltages, presents a stable high gain and sub-Poissonian noise levels. However, detectors had a large dark current (6μA at -1.5V bias), which made long integration times impossible. This was concluded to be due to the large active volume shared in between all devices.

By physically separating the detectors from each other, improving the fabrication conditions and material growth, internal dark current density of 0.1nA/cm2 at 160K has recently been achieved for detectors. This is three orders of magnitude lower than the value for best-reported eAPDs. We present our new studies on the transient response and timing resolution of detectors, which indicate 700 times improvement in bandwidth for 10μm injector diameter. Furthermore, our findings regarding the detector noise performance as well as the gain-bandwidth product relation with injector size will be presented. Our detailed simulation predicts achievement of 1Hz dark-count-rate at 90% photon-detection-efficiency at 190 K making the detectors strong candidates for PNR applications.

9220-17, Session 5

Dual behavior of optical antenna integrated with sub-wavelength photodetector to achieve ultra-high specific detectivity

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Fast photodetectors, with high sensitivity and quantum efficiency, are highly demanded elements for many modern applications, such as optical communication, optical interconnects, quantum key distribution, and infrared imaging. Therefore, it is crucial to optimize the quantum efficiency-bandwidth product, while maintaining a low noise. Integration of optical antennas with photodetectors leads to high quantum efficiency due to enhancing light – matter interaction as well as reducing the volume of the detector beyond diffraction limit. Although, a direct consequence of shrinking the detection size is the noise reduction, the local density of state (LDOS) will be enhanced in the near-field of optical antenna. LDOS enhancement can lead to an increased noise current, by reducing the carrier lifetime due to the enhancement of the radiative recombination rate. This effect could become significant especially for interband detectors, where the carrier lifetime is quite long compared with intersubband detectors. Here, we propose an antenna integrated with a deep sub-wavelength detector, which has a high quantum efficiency and low LDOS, leading to a very large specific detectivity. In order to achieve these features, we utilized dipole radiation/suppression concept as well as load matching concept at the nanoscale near-field of optical antenna.

9220-18, Session 5

Large area photodetectors based on InP NWs with InAs/InAsP QWs

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FPAs have a widespread use in imaging at SWIR (1-3µm), MWIR (3-5µm) and LWIR (8-14µm) wavelengths which often rely on cryogenic cooling to curtail the dark current level necessary for a reasonable signal-to-noise ratio, thus increasing the cost. QWIPs have the advantage of uniformity over large area but a severe drawback related to the selection rules for intersubband absorption, requiring integration with gratings for efficient light coupling. Self-assembled III-V nanowires have a key advantage owing to the enhanced absorption by optical resonance effects and the strain relaxation in NWs facilitating monolithic integration of different heterostructures.

We present electrical and optical results from large ensembles of n+-i-n+ InP NWs, axially grown on InP substrates with InAs/InAsP QWs embedded within the i-segment, designed for both interband and intersubband detection from SWIR to LWIR. The 130nm-diameter NW arrays are contacted in a vertical geometry using 50nm SiO2 as the insulating layer and ITO as the top contact. The interband photocurrent spectra from the QWs and NW matrix are consistent with the photoluminescence signals. The effect of n-doping on the device performance is studied by fabricating two different NW geometries, with and without an n+-segment grown before the nominal i-segment in the NW. In addition, the position of the QW within the i-segment is varied to further scrutinize effects related to doping and crystal structure. A comparison is made with thicker NWs (800nm diameter) to study resonant absorption phenomena at longer wavelengths. Finally, we also report on polarization dependence and results from sophisticated modeling.

9220-19, Session 5

Low-stress silicon nitride platform for broadband mid-infrared microphotonics

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We experimentally demonstrate a sophisticated mid-IR microphotonics platform adopting engineered Si-rich and low-stress silicon nitride (SiNx) thin films where an extensive infrared transparency up to ? = 8.5 µm is achieved. Furthermore, because of the designed low-stress property, the SiNx deposition is able to reach a thickness > 2 µm that significantly reduces mid-IR waveguide loss to less than 0.2 dB/cm. We show directional couplers functioning over a broad infrared spectrum, thus enabling monolithic mid-IR multiplexing schemes for integrated linear and nonlinear photonics leading to sophisticated label-free sensing technologies.

9220-20, Session 5

Frequency tunable photo-impedance sensor

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Using a transparent gate MOS structure in silicon, we construct a hybrid capacitive-resistive device (photo-impedance sensor), where a gated light sensitive semiconductor couples two or more fixed capacitances. Frequency dispersion in impedance of this optical semiconducting sensing element is used to tune the sensitivity and dynamic range of response. Upon illumination, the overall impedance is changed due to a change in resistance of the semiconductor and the capacitance of the MOS structure. The frequency dispersion makes the coupling of these capacitances sensitive to light intensity extending the senor dynamic range and tuning the sensitivity of the sensor. We present the results of modeling and simulations of this sensors and experimental data for a prototype device demonstrating advantages of this novel sensor in terms of sensitivity and dynamic range. The design and concept of this device could be extended to many other semiconductor materials, where frequency dispersion is related either to traps, or embedded nanoparticles or carrier generation processes.

9220-21, Session 6

Er3+/Yb3+ co-doped all-fiber Mach-Zehnder interferometer for 1550nm applications

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In this work an Er3+/Yb3+ co-doped all-fiber Mach-Zehnder interferometer that could be suitable for telecomm channel selection, temperature sensing or torsion sensing applications is proposed. The experimental array consists on a 980nm pump laser diode at 350mW output power, a 30cm co-doped fiber segment from our own design, and a couple of mechanically-induced long period fiber gratings in cascade on the co-doped fiber. The experimental results show an ASE operation bandwidth spectrum from 1450nm to 1650nm. The resulting interference pattern line-width is around 10nm with a 0.5dBm depth. The theoretical model based on Einsteins rate equations, along with the LPG in-house fabrication method, and full experimental results which were in good agreement with theoretical simulation, will be included in the manuscript.

9220-22, Session 6

All-fibre temperature sensing interferometer based on resonant frequency-shifting

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The resonant wavelengths-shifting caused by temperature variations in an all-fiber Mach-Zehnder interferometer is theoretically determined on a piece of fiber. Two long period fiber gratings were built on the rare-earth-doped fiber using a simple mechanical procedure. Wavelength tuning towards longer wavelengths can be controlled through its operating temperature and the material of the grating. The temperature change on the gratings modifies the spatial period of the grooves in accordance with the linear thermal expansion of the material used to build the LPFG. Spectral tunning of 0.9nm per 50 degree variation was observed when one LPFGs was temperature-controlled, while temperature variations on both the LPFGs showed 2nm spectral variation for a 100 degree Celcius span variation, which could lead to the development of accurate all-fibre sensing devices.

9220-23, Session 6

Fabrication of long period fiber gratings by electric arc for strain sensing applications

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Lately, there has been a huge demand for smart structures. Failure prevention requires an appropriate monitoring and maintenance system. Currently, there are available several types of sensors capable of detecting problems in structures. In recent times, sensors based on optical fibers have been proposed because they represent a non-invasive technique. Some optical fiber sensors are based on Bragg gratings. A grating is a periodical index perturbation of the fiber core which is most commonly achieved through UV radiation. Another technique to fabricate the gratings that has not been studied extensively is electric arc. Therefore, in this work we propose the use of this technique to fabricate fiber optical sensors based on Long Period Fiber Gratings (LPFG). Manufacturing LPFG through electric arc has the advantage of being quite flexible, inexpensive, they present very high temperature stability and can be applied to any type of optical fiber. LPFG with a period of 500 microns and 20 mm of longitude were fabricated through electric arc on standard monomode fibers with the help of a fusion machine and its spectrum observed by an Optical Spectrum Analyzer (OSA). This type of LPFG is tunable by changing the fabrication parameters of the electric arc which in turns will vary its sensitivity to measure strain on structures when it is used as sensor. Also, in this paper a theoretical and analytical examination of arc induced LPFG is presented. Complete mathematical analysis and simulation of the sensor based on LPFG were carried out using the software MATLAB/Simulink.

9220-24, Session 6

Pupil imager

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This system employs a combined midwave-longwave IR fore-optical assembly (400 mm focal length, F/2.3; Janos Technology) with an external pupil relayed into the Dewar cold space, a liquid nitrogen & helium Dewar with temperature-controlled low temperature stage (IR Laboratories, Inc.), an LWIR FPA with dark current that continues to decline as temperatures are lowered to 40 Kelvin (Teledyne Scientific Imaging), and a turnkey drive and data acquisition system optimized for the FPA (SE-IR Corp.). Broad waveband response (~3 to 12 um) results with the fore-optic that is optimized for both MW & LWIR, as well as from the anti-reflection coating on the field lens. Fast (10 Megapixel per sec, 14 bit) A-to-Ds in the SE-IR system support frame rates up to 120 Hz. Combining these items with several small optical components (a precision pinhole from National Aperture; a cooled IR lens for pupil reimaging from Edmund Scientific) results in a system with sensitivity that we quantify by single-frame detections of a distant blackbody cavity (e.g., one-inch diameter, 100 C blackbody at distances of several hundred meters). Integration times in excess of 10 millisec have been achieved with the Dewar cold stage operated at 50 Kelvin, and noise performance has been bracketed with single frames of data collected over several integration times and over several minutes duration. Also, the system has demonstrated immunity to pointing errors. Although operation to date has been with a lower operability, engineering grade FPA, plans will be described to eventually upgrade to a higher quality device.

9220-25, Session 6

An improved apparatus of infrared videopupillography for monitoring pupil size

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The intraocular pressure (IOP) can diagnose or track glaucoma generally because it is one of the physiology parameters that are associated with glaucoma. But IOP is not easy and consistence to be measured under different measure conditions. Hence an infrared videopupillography is needed to monitor the pupil size in an attempt to bypass the direct IOP measurement. Our previous research proposed an infrared videopupillography to monitoring the pupil size of different light stimulus in dark room. And this portable infrared videopupillography contains a camera, a beam splitter, the visible-light LEDs for stimulating the eyes, and the infrared LEDs for lighting the eyes. It can be mounted on any eyeglass frame. But it can modulate only two dimensions, we cannot zoom in/out the eyes. Moreover, the eye diameter curves were not smooth and jagged because of the light spots, lone eyelashes, and blink. Therefore, we redesign the optical path of our device to have three dimension modulation. Then we can zoom in the eye to increase the eye resolution and to avoid the LED light spots. The light spot could be solved by defining the distance between IR LED and CCD. This device smaller volume and less prices of our previous videopupillography. We hope this new infrared videopupillography proposed in this paper can achieving early detection about diabetic patients in the future.

9221-6, Session PMon

Research on construction of Web 3D-GIS based on Skyline

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This article describes a method that is based on Skyline Software to create a three-dimensional WebGIS. It includes data acquisition, data processing, three-dimensional scene creation, releasing to Internet and systems development. Furthermore, the paper selects a drainage basin in Shandong Province to elaborate feasibility and effectiveness of this method.

9221-7, Session PMon

Multi-angle polarized remote sensing of soot aerosol over China

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Soot aerosols are mainly emitted from incomplete combustion of fossil fuels and biomass burning, which are the mainly anthropogenic atmospheric aerosol. Due to the black carbon in soot aerosols that the dominant absorber of visible solar radiation, soot aerosols become the second most important component of global warming after carbon dioxide in terms of direct forcing. Soot aerosol has been known to be a source of significant uncertainties in studies of earth's climate, which is explained by difficulties in monitoring spatially- and temporally-variable aerosol properties. The only way to obtain the aerosol particles properties on a global scale is by means of satellite remote sensing. Multi-angle polarized measurements provide an alternative approach for the study the soot aerosol particles. The polarized surface contribution is smaller than, or equal to, that the atmosphere. Moreover it shows little spectral dependence and generally weak spatial contrast.

In this paper, the microphysical and optical properties of soot aerosol particles are studied, and the vector radiative transfer model coupling the BRDF model and BPDF model of surface reflectance was used study the TOA reflectance and polarized reflectance of soot aerosol. The sensitivity of reflectance and polarized reflectance to soot aerosol particles microphysical optical parameters are evaluated. Based on the studies of the sensitivity, the basic theory of using the remote sensing data of multi-angular polarized to retrieve the optical properties of soot aerosol is proposed. The conceptual aerosol retrieval was applied using the multi-angle polarized remote sensing data.

9221-8, Session PMon

Changes of building zones at the beginning of 21st century in Zhejiang Province, China

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Building Zone is the results of human activities, which is one of the most important input parameters for the simulation of biogeochemical cycle, and have very important significance for the research of earth system science. Therefore, it is very necessary to map the distribution of building zones and monitor the changes of it by using new technologies and methods at high spatiotemporal resolution. This article mainly explored the changes of building zones at the beginning of 21st century in Zhejiang Province, China, based on Geographic Information System (GIS) and Remote Sensing (RS). In the article, we first introduced the mapping processes of Land Use in the study area based on the method which combined object-oriented method and binary decision tree. Then, we analyzed the changes of building zones in the study area from 2000 to 2005 and 2005 to 2010. In addition to this, we also discussed the relationship between the increased building zones and their distance to road and river. Through the study of this article, we got that there were about 1564.07km2 and 1607.73km2 non-building zones turned into building zones from 2000 to 2005 and 2005 to 2010 respectively. Of course, the contrary conversion was also existed which accounted for 22.52km2 and 96.32 km2 respectively. However, the city with the greatest increase of building zones from 2000 to 2005 and 2005 to 2010 is Ningbo and Jiaxing respectively. Through the analysis of the increased building zones related to road or river, we also found that most of the increased building zones distributed nearby the road or river. .

9221-9, Session PMon

A new ocean color algorithm for suspended sediment concentration monitoring for East China Sea

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Suspended sediment concentration (SSC) is an important parameter of water quality and plays an important role in the global carbon cycle. The East China Sea is well known for its high SSC with some regions higher than 5000 mg/l, exceeding the ranges of many SSC algorithms. To overcome such limitation, a new SSC algorithm has been developed in this study. It takes advantage of characteristics of reflectance with SSC by combined several bands, thus enhancing the relationship between reflectance and SSC in a wide variation of concentration of sediment. It is used to retrieve SSC from in-situ measured reflectance with a mean relative error of 16.7%. This algorithm is used to retrieve SSC images from satellite data with a mean relative error of 19.6%, estimated by an average method that reduces the effects of SSC in temporal and spatial variations between in-situ measurement and satellite imagery. This algorithm is especially suitable for retrieving SSC from satellite data in high turbid coastal waters.

9221-11, Session PMon

Characterisation of aerosol types over China and its application in remote sensing *(Invited Paper)*

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China has experienced unprecedented economic growth over the past two decades characterized by the development of industries and anthropogenic activities. As a result, it has become one of the world's most dense aerosol regions. The complex source, composition of China aerosol contributes to the worst accuracy of aerosol radiative forcing assessment in the world. Aerosols in China show a great variety of shapes, often different from spheroids. Analyses of laboratory measurements and in situ data using scanning electron microscopes reveal that the mineral dust and carbonaceous soot particles are of complex morphologies rather than homogeneous spheres.

To improve the understanding of the aerosol types, to reduce the uncertainty of aerosol effects on climate change, and to improve the accuracy of quantitative remote sensing, a classification of China aerosol types is carried out via an improved hierarchical clustering analysis of optical properties obtained from inversion of sky radiance distribution at China AERONET stations, using data recorded over the last decade. The sphericity parameter is added in the development of aerosol model. The aerosols are categorized into 4 types. Based on the clustering analysis, the sensitivity of aerosol microphysical and optical parameters to TOA reflectance is evaluated.

The improved aerosol models are applied in the MODIS dark target inversion algorithm to retrieve AOT data at Xianghe site, results show a dramatic improvement of retrieval accuracy with compared to the MODIS official product.

9221-16, Session PMon

The application of satellite remote sensing data in the simulation of suspended sediment transport

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The distribution and transport of suspended sediment in the coastal areas has attracted more and more attention. Monitoring and modeling of the distribution and transport of suspended sediment is significant. The mutual promotion of remote sensing and numerical simulation play an import role on the coastal water quality study. In this study, a method of coupling derived suspended sediment image and numerical simulation, based on GOCI and COHERENS (COupled Hydrodynamical-Ecological model for REgioNal and Shelf seas) model, is proposed to simulate the suspended sedimet dynamics in the East China Sea. The retrieved suspended sediment concentrations were extracted from GOCI images, to set as initial condition and employed to calibrate the parameters and validation for the hydrodynamic modeling and sediment transport modeling, respectively. The model is forced by considering tidal surface elevation at open sea boundary, river discharges, surface stress as a function of wind speed, air temperature, relative humidity and cloud coverage, bottom roughness and heat flux through sea surface. The model results are in accord with the in situ measurements. The results show that: (1) Compared with the suspended sediment initialization of spatial-constant, the spatial-variant suspended sediment input can quickly response to the changes of sediment concentration in real sense. (2) Remote sensing is helpful to calibrate and validate the model for simulating the suspended sediment concentration. (3)The proposed approach can obtain reasonable simulated results in the East China Sea. (4) It is of great significance to combine remote sensing and numerical simulation together to study the water quality in the coastal areas.

9221-18, Session PMon

Geoscience information integration and visualization research of Shandong province, China based on ArcGIS engine

Mingzhu Xu, Institute of Geographical Sciences and Natural Resources Research (China); Zhiqiang Gao, Yantai Institute of Coastal Zone Research (China); Jicai Ning, Yantai Institute of Coastal Zone Research Chinese Academy of Sciences (China)

To improve the access efficiency of geoscience data, efficient data model and storage solutions should be used. Geoscience data is usually classified by its format or coordinate system in existing storage solutions. When the data is large, it is not conducive to search the geographic features. In this paper, a geographical information integration system of Shandong province, China was developed based on the technology of ArcGIS Engine, .NET, and Oracle. Four function modules were designed, including data management, thematic information management, information inquiring and statistical analysis. Different types of massive geoscience data is classified by its themes in the system. The characteristics of can be browsed and managed by thematic information make the system convenient for geographic researchers and decision-making departments to use the data.

9221-26, Session PMon

Monitoring the dynamic of suspended sediment using tower-based water spectrum observing system in the Hangzhou Bay

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It is difficult to understand the dynamic changes of suspended sediment in highly turbid waters like Hangzhou Bay from satellite and aboard ship for the global problem of atmospheric correction in case 2 water, low time frequency of satellite data and high cost of voyage in-situ measurement . Now a new operational system for autonomous above-water radiance measurements, different from SeaPRISM, called the Surface Acquisition Systems (SAS, 350-800nm), has the ability to collect spectrum by minutes, was deployed at the Haitianyizhou Tourist Tower in Hangzhou Bay and used for the research of dynamic changes of suspended sediment mainly driven by tide. The SAS data were compared with simultaneous data measured aboard ship using an ASD FieldSpec Spectroradiometer (350–2500 nm) under the tower for validation. We also made a detailed quality control. After quality control, the SAS values matched the ASD values well in both quantity and spectral shapes. The average absolute differences between the SAS and ASD determinations of water-leaving radiances (computed linearly) were less than 10% in the 350-800nm spectral interval. A similar comparison for normalized water-leaving radiances showed average absolute differences less than 8%.the result, in keeping with those produced by traditional ASD system, suggest the feasibility of SAS deployed on fixed platforms(towers, lighthouse, etc.) We also developed a regional empirical TSM algorithm that is applicable in extremely turbid waters. The minutes TSM derived from SAS show good relationship with the change of tidal suggest the ability of monitor high dynamic changes by SAS.

9221-27, Session PMon

Harmhul algal bloom detection with MODIS inherent optical properties products: a decision tree application

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The Inherent Optical Properties (IOPs) including absorption and scattering characteristics are the primary indicators of water and its constituents' variations. Along with significant progresses and achievements on the research of radiative transfer and semi-analytical remote sensing algorithms, several IOPs have already been generated and published as remote sensing products, and consequently those improvements will bring about various researches on application of IOPs in the near future. As widely known, conventional derived chlorophyll concentration has large uncertainty in coastal seawaters, especially high dissolved and particulate loading regions, and could not reflect the Harmful Algal Bloom (HAB) status in advance. When bloom causative algae bring a series of changes to water quality, it will certainly alter IOPs. In this paper the decision tree method was applied to the MODIS IOPs products along with other standard products in the East China Sea

in recent years to detect large HAB events. Results proved that single IOPs parameter or the combination of IOPs and other parameters from MODIS products, such as pigment absorption coefficient, backscattering to total absorption ratio, spectral band ratio, were able to classify HAB from normal seawaters, and even discriminate dinoflagellate and diatom types roughly. Theoretical and statistical analyses on measured data are made to interpret IOPs differences from algae cell diameter, refractive index, pigment composition and other aspects. In conclusion, the remote sensing IOPs products could be applied to detect HAB in coastal optical complex waters and decision tree was a practical tool for use.

9221-28, Session PMon

Retrieval of total suspended matter in highly turbid waters of Hangzhou Bay using polarizing spectra data

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The distribution of suspended sediment in the water has a huge impact on ecosystem .The polarizing spectral characteristic of the leaving-water radiance carrys more information of water components, which provides a new method for ocean color remote sensing inversion algorithm study. With the Hangzhou Bay and the East China Sea ship voyage, the field stations measurement use Field spectrometer ASD to survey the degree of polarization (DOP) of the leaving-water radiance and to research the different water bodies' polarizing characteristic and distribution of the upward radiance. The measurement results indicate that spectral polarizing characteristic and distribution of the upward radiance has a great relationship of the measurement spectral band and water components of Hangzhou Bay and East China Sea which dominanted by different factors. The suspended sediment concentration and distribution effects the degree of polarization of the upward radiance. The higher concentration of water suspended sediment, the lower degree of polarization of the upward radiance. The DOP of upward radiance is sensitive to the measurement spectral band. With the wavelength increasing, the maximal value of the DOP of upward radiance increases.

9221-29, Session PMon

Assessing coastline exploitation degree from multi-temporal Landsat images: Jintang Island, China

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Jintang Island, located in Zhoushan archipelago New Area, China, covers an area of ~76.4 km2. As the closest island to connecting the continental shore of Zhejiang and the eastern Zhoushan Island after the project of Zhoushan Tran-Oceanic Bridges, it has experienced great change during the past 40 years, and however little attention was paid to discuss the coastline change of Jintang Island. In this paper the coastline position was mainly extracted by combining histogram thresholding and band ratio techniques with visual interpretation supplemented, based on Landsat multi-spectral imagery in 1975, 1995 and 2014. And then the coastline exploitation degree for different periods was quantified from three index, coastline tortuosity, coastline artificial intensity and coastline dominant use type. The uncertainty for coastline extraction was controlled in one-pixel for each image. The results showed that the position of coastline accreted seaward since 1975. As the natural coastline was straightened, the proportion of artificial coastline has surpassed the natural coastline after 1995. Until 2013, the dominant coastline type has been changed as artificial coastline, mainly covering urban/ industrial and port coast. Using the linear weighted sum of the scores for the above three index, the total coastline exploitation degree was derived and further divided into four grades: extremely high exploitation intensity (EHEI), high exploitation intensity (HEI), median exploitation intensity (MEI) and low exploitation intensity (LEI). From the total coastline exploitation degree maps, we found Jintang Island got the LEI for 1975, the MEI for 1995 and the HEI for 2014. This indicates that it is facing increasing human intervention for reclaiming more coastal land to develop the marine economy

9221-30, Session PMon

Dynamic analysis on coastline and sea reclamation in the region around Bohai based on remote sensing images

Xiangyang Liu, Zhiqiang Gao, Jicai Ning, Qingshui Lu, Yantai Institute of Coastal Zone Research (China)

With 2 periods of standard false-color images as data sources, using remote sensing and GIS technology, dynamic change information extraction of the coastline and sea reclamation was completed in the region around Bohai through visual interpretation and artificial vectorization, and then this kind of information was studied deeply. The conclusions are as follows: (1) From 2000 to 2010, coastline of the region around Bohai shows an increasing trend, advancing to the sea rapidly; coastline change of the Beijing-Tianjin-Tangshan area is maximum; the advancing of coastlines of Liaoning and Shandong Province to the sea is obvious; human factors are key factors for the above change . (2) From 2000 to 2010, the sea reclamation area of the region around Bohai is rapidly increasing, the increase of Beijing-Tianjin-Tangshan region is the largest relatively and that of Shandong Province is the smallest; from the structure point of view, the area of sea reclamation for building ports is the largest and that of tideland reclamation is the smallest; different regions have different structures; social and natural factors together determine the evolution of sea reclamation. (3) To some extent, sea reclamation contributes to the increase in length of the coastline; different use types of sea reclamation have different influences on the coastline changes.

9221-31, Session PMon

Nuclear power plants in China's coastal zone: risk and safety

Qingshui Lu, Zhiqiang Gao, Jicai Ning, Yantai Institute of Coastal Zone Research (China); Wei Gao, Colorado State Univ. (United States)

Nuclear power plants are used as an option to meet the demands for electricity due to the low emission of CO2 and other contaminants. The accident at the Fukushima nuclear power plant in 2011 has forced the Chinese government to adjust its original plans for nuclear power. The construction of inland nuclear power plants was stopped, and construction is currently only permitted in coastal zones. However, one obstacle of those plants is that the elevation of those plants is notably low, ranging from 2 to 9 meters and a number of the nuclear power plants are located in or near geological fault zones. In addition, the population density is very high in the coastal zones of China. To reduce those risks of nuclear power plants, central government should close the nuclear power plants within the fault zones, evaluate the combined effects of storm surges, inland floods and tidal waves on nuclear power plants and build closed dams around nuclear power plants to prevent damage from storm surges and tidal waves. The areas with no fault zones and low elevation should be considered to be possible sites for future nuclear power plants if the elevation can be increased.

9221-32, Session PMon

Spatial-temporal analysis of coastline changes around Bohai Sea based on remote sensing in recent 20a

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The aim of this study was to analyze the dynamic changes of harbors in the region around Bohai from 1980 to 2010.With 4 periods of standard false-color images as data sources, using remote sensing and GIS technology, dynamic change information extraction of harbors was completed in the region around Bohai through visual interpretation and artificial vectorization. Results showed that (1) The size of harbors in the region around Bohai from 1980 to 2010. increased from 276km2 in 1980 to 1861km2 in 2010 with a total increment value of 574%; (2) From 2000 to 2010, harbors of the region around Bohai shows the fastest increasing trend; (3) Economic development were the main driving factors accounting for the increasing of harbors from 1980 to 2010.

9221-33, Session PMon

The study of the spatio-temporal changes of drought in the Mongolian Plateau in 40 years based on TVDI

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The vegetation degradation, drought and other environmental issues in the Mongolian Plateau have been as the hot spot in the study of the climate change and the ecological environment changes in Northeast Asia. Based on the NOAA AVHRR NDVI-PathFinder 10d remote sensing data of 1981-1999 and MODIS vegetation index and the surface temperature 16d data of 2000-2012, the study inverted Temperature and Drought Vegetation Index (TVDI) by the Ts-NDVI general space, their spatio-temporal distribution and changes were studied. The main results are: 1) the results of accuracy verification showed that, TVDI could reflect the trends of soil moisture condition, and could be used as the drought evaluation index; 2) there were about 51.51% of the whole area suffering drought, and it was severe in some years; 3) in the period of 1981 – 2012, the drought became more serious in the Mongolian Plateau; 4) in the whole growing season, the drought alleviates from April to August, and increased in September and October; 5) There is close relation between soil moisture and vegetation cover, Land use. Bare land, construction area and grassland were dominated by drought, The drought in construction area and grassland were followed. Forest and shrubland were dominated by moisture, but shrubland was drier than that in grassland.

9221-34, Session PMon

Retrieval of aerosol optical depth over the Yangtze River Delta with HJ-1 data

Lu Zhang, Runhe Shi, East China Normal Univ. (China); Yongming Xu, Nanjing University of Information Science and Technology, School of Remote Sensing (China); Long Li, Wei Gao, East China Normal Univ. (China)

Aerosol optical depth (AOD) is a key indictor of the atmospheric environment. It has great significance to obtain the spatial distribution information of AOD for atmosphere monitoring and pollution controlling. In this paper, the HJ-1/CCD and landsat/TM satellite data were employed to retrieve the AOD of the Yangtze River Delta, China. The land surface reflectance of blue band was extracted from the MODIS land surface reflectance product (MOD09), then corrected to both CCD and TM sensors to generate the surface reflectance database. According to the characteristics of the study area and the used data, multi-dimension look up tables were built by using the Second Simulation of Satellite Signal in the Solar Spectrum(6s radiative transfer model). The surface reflectance database and the calculated apparent reflectance of both sensors were applied to retrieve the AOD over the Yangtze River Delta. In order to evaluated the data quality of the two sensers, difference between the AOD values were analyzed. Then compared the retrieved AOD with the MODIS aerosol product and the AERONET ground based data. Among the 15 cities in the Yangtze River Delta, the spatial distribution of AOD was astudied. Shanghai showed the highest AOD mean value, and Zhoushan showed the lowest value. In general, Shanghai and Suxichang area had the most serious air pollution in the delta. As for different landcover types, urban area showed the highest mean value and standard deviation of AOD, followed by forest and cropland. The lowest mean value and standard deviation of the AOD was observed in water body.

9221-35, Session PMon

Retrieval of phycocyanin concentration in the eutrophic Taihu Lake

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Phycocyanin (PC) in the blue-green algae is usually used to detective the quantity of the blue-green algae, because of its special absorption at 620nm. The water is so turbid and euthrophic in Taihu Lake that the accuracy of some empirical models varies highly. The datasets were collected over a considerable range of optional properties, trophic status, and geographical locations in Taihu Lake. So it is very useful to find a model which can retrieve phycocyanin concentration in a good accuracy and has the best ability to adapt time changing. This study applied sigle band model, the ratio model R(λi1)/ R(λi2), the first-derivative model, empirical ratio model and the three band model R(λi3)/(R(λi1)- R(λi2)). The objectives of this paper are to (a) to build the five models using the data measured in May, 2010 to find which model is the best; (b) to try to build a new model-empirical named by the author; (c) to exam the five models by the dataset measured in May, 2010. Accuracy for all these models were measured by R2, RMSE and MAPS. The result is that the three-band model is the best one of them. Its RMSE is lest and it has the best ability to adapt time changing.

9221-36, Session PMon

Analysis of optimal narrow band RVI for estimating foliar photosynthetic pigments based on PROSPECT model

Hong Wang, Runhe Shi, Pudong Liu, Ming-Liang Ma, East China Normal Univ. (China); Wei Gao, East China Normal Univ. (China) and Colorado State Univ. (United States)

A large number of leaf reflectance spectra with different photosynthetic pigments contents were simulated via PROSPECT model, and the data precision has reserved two decimal fractions. In order to select the fittest two-band combinations of narrow band RVI used in the inversion of photosynthetic pigment contents at leaf level, the range of 400-2500nm was traversed with 1nm as the band width. The methods of testing all possible combinations of narrow band RVI are comparing the correlations with the particular pigment contents and analyzing anti-interference ability to other leaf biochemical constituents. The results showed that: (1)At the leaf level, the narrow band RVI for the inversion of chlorophyll content do exist, whose two bands' ranges are: 434-454nm can combined with 550-589nm, 616-663nm or 738-747nm; 569-615nm can combined with 650-691nm. While the narrow band RVI for the inversion of carotenoid content do not exist. (2) There are two rules should be

followed: the interference of the selected bands from other biochemical constituents must be as low as possible, and the sensitivities of the two selected bands reflectance to the particular pigment must be greatly different.

9221-37, Session PMon

The impacts of bandwidths on the estimation of leaf chlorophyll concentration using normalized difference vegetation indices

Mingliang Ma, Runhe Shi, Pudong Liu, Hong Wang, Wei Gao, East China Normal Univ. (China)

The vegetation indexes are usually based on ground measured high-spectral data or other satellite data such as MODIS data.This is about a new method to acquire vegetation index .We should achieve the ground measured high-spectral vegetation data .Then we need the band responding function of GaoFen-1 Remote Sensing satellite of China.From the ground high-spectral data and band responding fuction ,We can get the broader band data.We can get some new vegetation index from the data we geted.

9221-38, Session PMon

the data fusion of aerosol optical thickness using universal kriging and stepwise regression in East China

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The obtaining of precision, full coverage aerosol optical thickness (AOT) is of great significance in the field of atmospheric environment research because AOD can characterize atmospheric turbidity effectively. The process of data fusion has the ability to maximize the advantages of all the raw data and minimize their disadvantages. We used the universal kriging (UK) data fusion method to combine the MISR AOT and MODIS AOT from Terra satellite in the East China, the results show a better consistency with AERONET AOT which is considered to be close to the true value than the MISR AOT and MODIS AOT with AERONET AOT, and the fusion results have an obvious seasonal variation. We had also analysis the variance of the data, it is showed that the MODIS AOT variance is higher than that for MISR, across all seasons. This is due in part to the fact that the more frequent and finer-scale MODIS sampling captures more small-scale AOT variability than MISR, The second reason for this higher variance is due to its exclusively near nadir viewing geometry, MODIS has a greater sensitivity to variability in surface brightness on small spatial scales, which in turn introduces some additional variability into the MODIS AOT retrievals. When strong correlation exists between MISR AOT and MODIS AOT, the universal kriging method can be used to obtain better predictions with smaller uncertainties relative to estimates based on measurements from a single sensor. But during the summer, less than 75% of the estimated AOT values are below the observed median of AERONET, indicating that kriging underestimates high levels of AOT. Also, the kriging model overestimates lower values of AERONET AOD in winter. But we can deal with this problem through combing different data fusion methods such as UK and FRK.

9221-39, Session PMon

The temporal and spatial relationship between the urban heat island intensity and the LUCC

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The changes of land use in urban surface, will inevitably affect the urban climate. Based on landsat TM images of 2001 and 2005, obtained the LUCC(land use and land cover change) conditions in Shanghai, combined with 10 meteorological stations daily meteorological data. We analyzed the spatial and temporal variations of urban heat island in different seasons, different months and different day times. Provide a reference for the research of urban environment and urban planning.

9221-40, Session PMon

Analysis on the balance between supply and demand of cropland in Yantai City of China in 2020

Qiuxian Wang, Yantai Institute of Coastal Zone Research (China) and Univ. of Chinese Academy of Sciences (China) and Ludong Univ. (China); Zhiqiang Gao, Yantai Institute of Coastal Zone Research (China); Jicai Ning, Yantai Institute of Coastal Zone Research,Chinese Academy of Sciences (China); Ye Wang, Institute of geography and planning, Ludong University (China)

With the fast development of economy and urbanization, the phenomenon of city construction occupying Cropland often happenes. As the contradiction between human and land becomes more prominent, the contradiction between the suppy and demand of the cropland are more radical in Yantai City of China. Analysis on the balance between supply and demand of cropland is the main basis to determine land use objectives, and also the basis of editting land use planning. In this paper, the authors firstly calculated the potential of cropland supply in Yantai for 2020 according to its current number of the cropland and the potential quantity of other kinds of land changing to the cropland, and then calculated the demand for cropland in 2020 with the methods of the population prediction and its national economic development planning. Then the balance between the supply and demand of cropland was analyed. The resutls were that the cropland in Yantai city in 2020 were lower than those of its demand. At last, to relieve the controdiciton, the authors tried to put forward some recommendations like optimizing the structure to coordinate the balance between the supply and demand of the cropland etc. to realize its regional sustainable developmnet.

9221-41, Session PMon

Examining the effects of increasing land price on urban sprawl in China coastal provinces during 1990-2010

Qingshui Lu, Yantai Institute of Coastal Zone Research (China)

Not long ago, China land was owned by state governments and it wasn't considered as asset for producing economic wealth. In the late 1980s, central governments issued series of polices that caused the ownership separate from land-use rights and the conversion of rural land to urban land was charged. Due to government regulations, land prices were still at low and stable level during 1990-1999. House distribution polices were completely changed in urban areas at the end of 1999 and caused land prices to rapid increase. By analyzing dynamics of urban sprawl, we found that increasing land prices caused urban sprawl accelerate during the period 2000-2005 and get slower during the period 2005-2010. But the most important driving force is different and the trends of urban sprawl are also different at different city levels. To balance urban sprawl and food safety, governments should issue new police according to these differences.

9221-42, Session PMon

The grain production potential assessment with multiple cropping index (MCI) in China

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Abstract: This paper retrieved the information of cropland and MCI (Multiple Cropping Index) of China in 2000 and 2009 with SPOT NDVI time series data and utilized meteorological data and statistical data released by the state to calculate potential MCI and statistical MCI. Then, the MCI potential of China and grain production potential based on MCI were calculated in order to analyze the potential spatial distribution characteristics of MCI and the potential spatial pattern characteristics. The improvement of MCI potential not only increases hydrothermal utilization rate and the utilization rate of cropland but also enormously enhances the food security degree of China and provides more available cropland area for the economic development.

9221-43, Session PMon

Spatial-temporal Variability of Coastline in Bohai Rim Based on Fractal Dimension

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Taihang Mountain in Hebei Province was chosen as the study area. Additionally, the remote sensing images of Landsat TM in 1990?2000 and 2008 were used as the main date source. The ecological risk index was constructed based on the calculation of the landscape structure indices, and the distribution level of ecological risk was mapped based on ecological risk index values by GIS and Geostatistics. The ecological risk of studying area was classified into five levels, i.e., extremely low ecological risk, low ecological risk, medium ecological risk, high ecological risk and extremely high ecological risk by relative index method. Afterwards the spatial-temporal variation characters of ecological risk distribution were quantitatively analyze by making the layer algebra operation of ecological risk maps in different periods. Results showed that the landscape ecological risk showed a downward trend in the past 18 years, with the main principle that distribution increased successively from the western high mountains to the eastern plains, in the obvious zonal structure. Extremely low and low risk areas distributed mainly in the western mountainous areas; Medium risk area was mainly in the mountain-plain-transition-belt; Extremely high and high risk areas distributed in the rural-urban ecotone, land around lakes and reservoirs; The Huangbizhuang reservoir and the east-central part of Shahe city were highest. To promote sustainable development of the ecological environment and the social economy, ecological protection and construction should be strengthened in the areas with intermediate ecological risk in the Taihang Mountains in Hebei Province.

9221-44, Session PMon

Comparison of the Hargreaves-Samani equation and the Priestley-Taylor equation for estimating reference crop evapotranspiration in the North China Plain

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Based on the climatic data including daily mean wind speed, average relative humidity, sunshine percentage, maximum and minimum temperature from 1960 to 2013 of 14 weather stations in Shandong Province, according to the Penman-Monteith model of Food and Agriculture Organization of the United Nations, the temporal and spatial structure and changes of evapotranspiration in Shandong Province were discussed. Evapotranspiration in summer was higher than that of other seasons. It was also found that the temporal trend of evapotranspiration in Jinan weather station was a high value year followed by a relatively low value year, namely it was showed a biennial cycle. Evapotranspiration of other region in Shandong Province outside the weather station was obtained by using Kriging interpolation method. Evapotranspiration had much to do with the vegetation and water. The maximum evapotranspiration was found in area with abundant water. In views of the changes of evapotranspiration in every year in typical stations, there presented regional differences. In eastern and southern Shandong Province, Evapotranspiration was higher than that in the middle.

9221-45, Session PMon

A WebGIS-based system for analyzing and visualizing air quality data for Shanghai Municipality

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This paper aims to introduce a construction of meteorological information management and service system based on WebGIS for Shanghai Municipality. Through the analysis of ArcGIS Server and its characteristics, we designed the overall scheme of the construction of the system, put forward the software and hardware environment in the construction of the system, determined the overall structure and the main function to be completed of the system. Finally, based on the Java programming environment, we designed the system with the Div + CSS layout combined with JSP, JavaScript, and some other computer programming languages.The system constructs a dynamic display platform of meteorological information based on ArcGIS Server, which mainly includes the organization and management of the map data and meteorological data, the release and management of map service, as well as the development of web sites. The system has successfully realized intensification, automation, and graphics of the displaying and sharing of the meteorological information.With which, we can release the information on the network by the intuitive and graphic way of graphics and texts. At the same time, the system has up-to-date information sharing and provides reminder and alerting capabilities.

9221-46, Session PMon

Estimating leaf photosynthetic pigments information by stepwise multiple linear regression analysis and a leaf optical model

Pudong Liu, Runhe Shi, Hong Wang, Kaixu Bai, East China Normal Univ. (China); Wei Gao, East China Normal Univ. (China) and Colorado State University (United States)

PROSPECT model was used to simulate leaf carotenoids content of vegetation changes from 0 to 2μg/cm-2 to observing the leaf spectral characteristics, linking to the FCR model to simulate leaf LAI of different area. Using “multiple stepwise regression analysis” method, the content of different biochemical parameters under the condition of establishing the carotenoids content, leaf reflectance and its changes of multivariate linear regression model, we evaluate the precision with the help of the multiple correlation coefficient and root mean square, through the analysis. we can get the conclusion that under the condition of a certain content of biochemical parameters, carotenoids prediction accuracy presents a trend of increasing with the increase of LAI.

9221-1, Session 1

Impact of teleconnection phenomena and local environmental factors on forest greenness in North and Central America *(Invited Paper)*

Ni-Bin Chang, Univ. of Central Florida (United States)

Not only the non-stationary teleconnection signals between sea surface temperature at the Atlantic and Pacific Oceans but also varying continental gradients, geographical and meteorological contexts, and interocean contrast may effect the terrestrial responses in pristine forested land. The growth of forest is critically vulnerable to the change in rainfall and radiation than in air temperature. Yet, the influence of the Atlantic and Pacific climate variability as well as local environmental factors on forest greenness through the North and Central America has not been well investigated and compared. This study uniquely integrates the hydroclimatic teleconnection phenomenon at the global scale and land surface temperature, precipitation, and albedo at the local scale to compare the terrestrial ecosystem response across three types of forested land. Different results were obtained from three site investigations, including Selway-Bitterroot (Northwest America, USA), Adirondack park (Northeest America, USA), and La Amistad International Park (Panama, Central America) are integrated for a comparison to illuminate the essence of forest sustainability. Remote sensing images collected by AVHRR, MODIS, TRMM, ASTER, and local meteorological stations are grouped together to analyze the proposed science questions. By comparing three forest types that may be affected by leading teleconnection patterns and those environmental factors based on the wavelet analysis, the phenology of pristine forests across varying continental gradients, geographical and meteorological contexts, and interocean contrast may become understandable.

9221-2, Session 1

Hurst exponent for fractal characterization of satellite images

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In this research we show the application of Hurst exponent (H) for fractal characterization of satellite images. The Hurst exponent, whose values are in the range $0< H<1$, quantifies the relative tendency of a time series to regress to the mean or to cluster in a specific direction. Given that the estimation of H has been useful in a variety of fields, such as finance and physiology, there exist different algorithms for this purpose. Among the methods frequently used in the literature, we focus on an approach based on a generalized high-dimensional variance around a moving average low-pass filter, which is fast and ease of implementation. From a d-dimensional signal, the algorithm first generates an average response for different subarrays by varying the size of the moving low-pass filter. For each subarray the corresponding variance value is calculated by the difference between the original and the averaged signals. The variance obtained at each subarray is then plotted on log-log axes and the slope of the regression line corresponds to the Hurst exponent. Hence, the application of the algorithm to a set of time sequence imagery, registered by LANDSAT, has allowed us to quantify the Hurst exponent of specific areas on Earth surface. According to our results, the H value is directly related to the changes in land use, performing a decreasing H value when the area under study has been modified. In particular natural areas showing a gradual growth of man made or those showing an increasing degree of pollution, have a considerable decrease in their corresponding Hurst exponent.

9221-3, Session 1

Assimilation of remote sensing data into crop growth model to improve the estimation of regional winter wheat yield

Chaoshun Liu, Wei Gao, East China Normal Univ. (China)

Regional crop production prediction is a significant component of national food security assessment. Remote sensing has the advantage of acquiring soil surface and crop canopy radiation information, however it is hard to reveal the inherence mechanism of crop growth and yield formation. Crop growth models based on the crop photosynthesis, transpiration, respiration, nutrition are successfully applicable for yield forecasting in simple point scale, however, they are hampered by the deriving of regional crop key input parameters. Data assimilation method which combines crop growth model and remotely sensed data has been proved the most potential approach in regional yield estimation. Based on the calibration and regional of WOFOST, the WOFOST model had been used to express the characteristic of time series LAI in crop growth season. Time-series LAI was assimilated through combined corrected MODIS-LAI and WOFOST simulated LAI from green-up to heading stage with EnKF algorithm. The assimilated optimal LAI was used to drive the WOFOST model per-pixel to estimate the regional yield. The results showed that assimilation of the remotely sensed data into crop growth model with EnKF can provide a reliable approach for prediction regional crop yield and had great potential in agricultural applications. The research can provide an important reference value for the regional crop production estimation.

9221-4, Session 1

Spatial discretization of distributed hydrological response units for SWAT

Jicai Ning, Zhiqiang Gao, Yantai Institute of Coastal Zone Research (China)

The world is experiencing increasingly more serious situation of water resources. The distributed hydrological model (DHM) has become the indispensable means for exploring the influences of climate change and human on hydrological cycles and water resources. With strict mathematical and physical description of hydrological processes, DHM could account the spatial variations of watershed parameters and horizontally relate different HRUs. Therefore, the Digital Terrain Model (DEM) based DHM is one major trend of hydrological modeling. Theoretically, the absolutely physical DHM is built on the strict hydrological processes. However, none of current DHMs can absolutely describe the strict hydrological processes, and most are based on some hypotheses. For the semi-distributed hydrological model, Soil and Water Assessment Tools (SWAT), Hydrological Response Units (HRU) is the basic modeling unit, defined by land use, soil and slope. Land surface patches within one Hydrological Response Units (HRU) should bear identical hydrological properties (including land use, soil, slope and management) and thus have similar hydrological responses. However, it is difficult to determinate the spatial locations and to describe the interactions between different HRUs. This study proposed one schema to discretize HRU for SWAT on the basis of generalized data input. Within a small watershed of Taihu Basin, the data of land use and soil were generalized for discretizing SWAT HRUs. The SWAT model was modified with the discretized HRUs. The resulted showed that the SWAT improved by discretization schema could be more sensitive the runoff lag process and thus achieved better simulation accuracy.

9221-5, Session 1

Investigation of atmospheric insect wing-beat frequencies and iridescent features using a multi-spectral kHz remote detection system

(Invited Paper)

Alem K. Gebru, Stellenbosch Univ. (South Africa); Mikkel S. Brydegaard, Stellenbosch Univ. (South Africa) and Lund Univ. (Sweden); Erich G. Rohwer, Pieter Neethling, Stellenbosch Univ. (South Africa)

Quantitative investigation of insect activity in their natural habitat is a challenging task for entomologist. It is difficult to address questions such as flight direction, predation and over all activities of fast events and huge numbers using the current techniques, e.g. different kind of traps and sweep nets have instrument biases with regards to the size and species of insect being cached. Implementation of optical remote sensing tool can provide reliable information to study activity and abundance of insects. Such techniques have the potential to remotely determine: species, sex, predation strength, reflectance, fluoresces properties and overall activity of insects. Wing-beat frequency and iridescence features of insect can also be determined remotely. We have developed and tested passive remote sensing tool to determine wing beat frequency, optical cross-section (OCS) and iridescence features. The main principle of this work is dark-field spectroscopy and we tried to achieve minimum back ground measurement. This experiment is a novel 10 kHz, three-band spectrometer, which covers the visible (VIS), near infrared (NIR) and short wave infrared (SWIR) ranges. The extent of resolving wing-beat modulation of fast insect events depends on the sampling frequency. We have implemented fast sampling frequency, which enabled us to resolve wing beat modulation as well as higher order harmonics. We found that the difference in wing-beat trajectory, wing-beat modulation and Absolute Optical cross-section can be used as a tool to identify and classify insect species remotely. This study gave us some insight towards future investigation of quantifying wing membrane thickness of insects.

9221-10, Session 1

Monitoring of land- and sea-use in Zhoushan Islands, China by an spectral rule-based pre-classification approach

Zhu Li, Jianyu Chen, Zhihua Mao, Haiqing Huang, Xiao Ping Zhang, The Second Institute of Oceanography, SOA (China)

The Zhoushan Islands is located on the middle eastern tip of China Coast. An area which was traditionally best known for its fishing and tourism, it has in recent years undergone a transformation with the intensification of strategic industrial enterprises and an ensuing shift in the type of land and sea use activities concentrated in this area. For monitoring of current land- and sea-use in Zhoushan Island, an automatic pre-classification approach is used in this paper, which is the downscaled from a literature proposed by Baraldi et al.. It is a spectral rule-based per-pixel classifier, requiring no training and supervision to run. As input features, the four bands of the SPOT5 are calibrated into planetary reflectance values. To capture properties of the spectral signature of target object, features should be extracted and consist of three portions. The first part like Brightness (Bright), visible reflectance (Vis), near-infrared reflectance (NIR) and middle infrared reflectance (MIR) is computed as ratios between spectral data or linear combinations of spectral bands. In addition, the second part consists of surface type indexes like normalized difference vegetation index (NDVI), normalized difference bare soil index (NDBSI), normalized difference snow index (NDSI) and normalized difference built-up areas and barren land index (NDBBBI). The third part is spectral rules which defined by calibrated band-values with relational operators. Then to get fuzzy sets from these extracted features. Finally, the pre-classes can be acquired by implementing hierarchy of logical function with the fuzzy sets. Based on the GDAL library programming, the pre-classes are acquired. Compared with the supervised classification samples, the accuracy of results obtained by pre-classification method is good. Additionally, this approach is computationally efficient and more detailed classification.

9221-13, Session 2

Assimilation of soil moisture using Ensemble Kalman Filter

Juan Du, East China Normal Univ. (China); Chaoshun Liu, Key Laboratory of Geographic Information Science, Ministry of Education, East China Normal Universit (China) and Joint Laboratory for Environmental Remote Sensing and Data Assimilation, ECNU & CEODE (China); Wei Gao, Key Laboratory of Geographic Information Science, Ministry of Education, East China Normal Universit (China) and Joint Laboratory for Environmental Remote Sensing and Data Assimilation, ECNU & CEODE (China) and USDA UV-B Monitoring and Research Program, Natural Resource Ecology Laboratory, Colorado State Unive (United States)

In this paper, soil temperature and moisture data assimilation scheme is developed based on Ensemble Kalman Filter (EnKF) and Community Land Model version 3.0 (CLM), which is mainly used to improve the estimation of the surface heat and water fluxes by assimilating in situ observations. The temperature and moisture of nine soil layers are updated. The paper discusses the effect of assimilating different observations, number of ensembles, assimilation frequency on the model result. The scheme is tested and validated based on measurements in Arou. Results indicate that data assimilation method improves the estimation of surface heat and water fluxes, especially the sensible heat flux. Assimilating soil moisture was more effective than assimilating soil temperature. What's more, assimilation results are more stable when the ensemble number is more than twenty. Soil temperature is more sensitive to assimilation frequency than the soil moisture. It also illustrates the meaning of assimilating soil moisture.

9221-14, Session 2

Optical methods for control of hydrogen influence on plants

Elena V. Timchenko, Nikolay V. Tregub, Larisa A. Taskina, Ekaterina A. Selezneva, Pavel E. Timchenko, Samara State Aerospace Univ. (Russian Federation)

A factor that complicate ecological situation is degassing of earth, namely the release of radon, helium, hydrocarbons and molecular hydrogen mixture along active faults lithosphere. In turn the plants can be sensitive marker of environmental change.

The experimental study of the hydrogen influence on optical characteristics of plants by Raman spectroscopy and fluorescence confocal microscopy was performed. The parsley (Petroselinum) and pea (Pisum sativum) were used as objects of research. The plants were grown in the laboratory greenhouses where climate conditions, regularity and constancy of light flux were identical for all plants. The plants were divided into next groups: control plants group and plants groups that were growing with high content of various hydrogen concentrations in soil (1% and 2% hydrogen). Experiments also were carried on similar plants groups (pea) growing by hydroponic method. This was performed to exclude the influence of CO_2 and soil bacteria secretions on the plant characteristics.

The experimental stand that implements Raman spectroscopy included radiation source, radiation input and output fiber system, Raman probe InPhotonics RPB785 and SR-303i spectrograph (focal length of 303 mm) with ANDOR DV-420A-OE integrated digital camera (1024*256). The experimental stand allows working with radiation in the spectral range of 180 - 1200 nm with the measurement error of 0.2 nm. The confocal

fluorescent microscopy stand consisted of light source, optical focusing system, confocal unit and recording camera (1024x1024, exposure time 40 ms).

The research results are the following:

1) Raman spectrum features of plants under the influence of hydrogen were received. Shown that with 2% hydrogen concentration the Raman amplitude intensity increases at wavenumbers 1130 cm-1, 1495 cm-1, which is associated with increase glucose, starch and carotenoids;

2) Structural changes in a plant leaf under the hydrogen influence was revealed using confocal fluorescent microscopy.

9221-15, Session 2

Using NOAA/AVHRR based remote sensing data and PCR method for estimation of Aus rice yield in Bangladesh *(Invited Paper)*

Mohammad Nizamuddin, The City College of New York (United States); Kawsar A. Akhand, The City Univ. of New York (United States); Leonid Roytman, The City College of New York (United States); Felix Kogan, Mitch Goldberg, National Environmental Satellite, Data, and Information Service (United States)

Rice is a dominant food crop of Bangladesh accounting about 75 percent of agricultural land use for rice cultivation and currently Bangladesh is the world's sixth largest rice producing country. Rice provides about two-third of total calorie supply and about one-half of the agricultural GDP and one-sixth of the national income in Bangladesh. Aus is one of the main rice varieties in Bangladesh. Crop production, especially rice, the main food staple, is the most susceptible to climate change and variability. Any change in climate will, thus, increase uncertainty regarding rice production as climate is major cause year-to-year variability in rice productivity. This paper shows the application of remote sensing data for estimating aus rice yield in Bangladesh using official statistics of rice yield with real time acquired satellite data from Advanced Very High Resolution Radiometer (AVHRR) sensor and Principal Component Regression (PCR) method was used to construct a model. The simulated result was compared with official agricultural statistics showing that the error of estimation of aus rice yield was less than 10%. Remote sensing, therefore, is a valuable tool for estimating crop yields well in advance of harvest, and at a low cost.

9221-17, Session 2

Optical identification of diatom bloom based on MERIS measurement in the East China Sea

Bangyi Tao, Zhihua Mao, The Second Institute of Oceanography, SOA (China); Hui Lei, Hangzhou Normal Univ. (China); Qiankun Zhu, Haiqing Huang, The Second Institute of Oceanography, SOA (China)

Identification of phytoplankton groups from ocean color data is still a challenge work in coastal waters. Recently, significant differences between the absorption characteristics of algal bloom dominated by diatom and those of dinoflagellates from the East China Sea have been found, especially in the red-wavelength range. It is suggested that these differences could introduce distinguished spectral features in remote sensing reflectance (Rrs). Therefore, a multispectral approach for discriminating the diatom blooms from dinoflagellate ones has been developed based on MERIS Rrs spectral shape discrimination. The procedure is separated into two steps. Firstly, the Rrs line height at 681 nm (LH681) and 709 nm (LH709) above a baseline through the measurements at 665 nm and 753 nm are calculated. The Rrs(560) and the ratio of LH709 to LH681 are used to separate bloom waters from clear and turbid ones, due to the relatively low reflectance in the green band of algal bloom waters and the reflectance peak position shift in the red band. Secondly, it is found that the spectral absorption of the diatoms show a much stronger spectral slope than that of dinoflagellates in the 645 ~ 675 nm spectral domain, and thus two spectral Rrs slopes, Rrs(620) - Rrs(665) slope and Rrs(665) - Rrs(681) slope, are used to discriminate the diatom blooms from dinoflagellate ones. We strongly suggest that the diatom blooms can be successfully identified with the MERIS imagery, which have been confirmed by field sampling to contain high cell concentrations.

9221-19, Session 2

Calibration of significant wave height from HY-2A satellite altimeter

Jingsong Yang, Guangjun Xu, Yuan Xu, Xiaoyan Chen, The Second Institute of Oceanography, SOA (China)

In order to improve the consistency of sea surface wind speed (SSWS) data from different satellite altimeters, the SSWS data from HY-2A, T/P, GFO, Jason-1/2, Envisat, and CryoSat-2 satellite altimeters are compared with NDBC buoy data. Then, the calibration formulas are given, and the calibration results are investigated. The results show that both the mean values (MVs) and root mean squares (RMSs) of the differences between the SSWS data from the satellite altimeters and from the buoys decrease after the calibrations, especially for the case of HY-2A satellite altimeter. The MVs are within ±0.2 m/s, and the RMSs are below 1.6m/s except for the HY-2A, GFO, and Jason-1 satellite altimeters. Therefore, the calibration formulas presented in this paper are useful for reducing the differences between the SSWS data from the satellite altimeters and from the buoys.

9221-20, Session 3

Crude oil remote sensing, characterization, and cleaning with CW and pulsed lasers *(Invited Paper)*

Nickolai V. Kukhtarev, Tatiana V Kukhtareva, Alabama A&M Univ. (United States); Sonia C Gallegos, NASA/ASTPO Stennis Spaceflight Center (United States); Arcadi Chirita, Moldova State University (Moldova)

For detection, identification and characterization of crude oil we suggest to combine several optical methods of remote sensing of crude oil films and emulsions (coherent fringe projection illumination (CFP), holographic in-line interferometry (HILI), laser induced fluorescence,). These methods allow to make three-dimensional characterization of oil spills, that is important for practical applications.Combined methods of CFP and HILI are described in the frame of coherent superposition of partial interference patterns. It is shown, that in addition to detection/identification laser illumination in green-blue region can also degrade oil spills. Different types of the surfaces contaminated by oil spills are tested: oil on the water, oil on the flat solid surfaces, oil on the curved surfaces as pipes. For the detection and monitoring of the laser-induced oil degradation in pipes coherent fiber bundles were used. Both continuous-wave (CW) and pulsed lasers are tested using pump-probe schemes. This finding allow to suggest that properly structured laser clean-up can be alternative environmently-friendly methods of decontamination and cleaning, as previously used chemical methods are dangerous to environment.

9221-21, Session 3

Linkages between turbidity levels in Lake Mead associated forest fire events in the lower Virgin watershed *(Invited Paper)*

Ni-Bin Chang, Univ. of Central Florida (United States)

Turbidity is one of the drinking water quality indexes as Lake Mead is the major tap water source in Las Vegas. As a result of threat posed to drinking water of 25 million people downstream, recreation area, and wildlife habitat of Lake Mead, it is necessary to develop a method for near real-time monitoring of turbidity in Lake Mead area. Monitoring through a limited number of ground-based monitoring stations on a weekly/monthly basis is insufficient to capture both spatial and temporal variations of water quality changes. In this study, remote sensing technology with the aid of data fusion and mining techniques provides us with information about the spatiotemporal distribution of turbidity for the entire lake on a daily basis. A data fusion method was applied to bridge the gap of poor 250/500m spatial resolution for the land bands of Moderate Resolution Imaging Spectroradiometer (MODIS) imageries with the 30 m enhanced spatial resolution of Landsat's imageries which suffers from long overpass of 16 days. Consequently, Integrated Data Fusion and Mining (IDFM) techniques produce synthetic fused images of MODIS and Landsat satellites with both high spatial and temporal resolution in order to create near-real time turbidity distribution maps and lead to sustainable water quality management with the aid of IDFM in Lake Mead monitoring analysis associated with the forest fire events in the Lower Virgin watershed to identify event-based pollution episode in Lake Mead.

9221-22, Session 3

Study of emissivity behavior in soil through medium infrared range images

Carlos Villaseñor-Mora, Arturo González-Vega, Haydee Hernández-Arellano, A. Jacqueline Chávez-Martínez, L. Fernando Avilez-Pérez, Univ. de Guanajuato (Mexico)

Although the emissivity behavior of soil moisture has been the subject of numerous research works, making a critical survey of published results, it is possible to find some inconsistencies and general paucity of the quantitative data on which to base observations. The works establish that the initial effect of increasing soil moisture is principally reduce reflectance and increase emissivity, it is maybe caused by the quartz, the main component of the studied soils, but when sufficient moisture is present to result in a continuous film of water on the soil grains at the surface, the spectrum abruptly becomes that of water. This work was conducted using the direct method for measurement of emissivity, comparing the energy obtained from an infrared image of soil to the energy obtained from an infrared image of a blackbody at the same temperature as the soil sample, and, unlike with the indirect method through reflectance, different results were obtained. A dozen of different kinds of soil from the region were analyzed, at different moisture levels and it was found that in all of them, as the moisture content increases, emissivity of the sample decreases, which in turn results in a behavior that is different to that described in several previous research works.

9221-23, Session 3

Evaluation of CALIPSO aerosol optical depth using AERONET and MODIS data over China

Chaoshun Liu, East China Normal Univ. (China)

The objectives of this study are to investigate major climate factors affecting the distribution of rice planting region in China based on the maximum entropy model (MaxEnt) and the spatial analysis function of ArcGIS software. The potential rice planting distribution and its response to climate change are revealed as well according to the existence probability from MaxEnt model. The results can provide reference for rice planting pattern and countermeasures to cope with climate change impact on China?

9221-24, Session 3

Spatio-temporal distribution of NDVI and its correlation with climatic factors in Eastern China during 1998-2008

Cong Zhou, Runhe Shi, East China Normal Univ. (China); Chao Zhang, East China Normal Univ (China); Chaoshun Liu, East China Normal Univ. (China); Wei Gao, East China Normal Univ. (China) and Colorado State Univ. (United States)

As one of the most important greenhouse gases, carbon dioxide (CO2) has been observed for a long time by ground-based stations and satellites. However, satellites observe CO2 at different sensitive altitudes. Atmospheric Infrared Sounder (AIRS) is sensitive to mid-troposphere while Greenhouse gases Observing SATellite (GOSAT) sensitive to near surface. The difference of CO2 mixing ratios between the surface and a given altitude is determined by the processes that transport surface air throughout the atmosphere. This paper displays the correlation of CO2 retrieved by AIRS and GOSAT from 2010 and 2012 using correlation analysis and stepwise regression methods. Climatic factors such as temperature, relative humidity from NCEP reanalysis project are also used as the covariates. The correlation coefficient of AIRS and GOSAT CO2 in China is low, which indicates an uncertain relationship between CO2 at surface and mid-troposphere. Further results from stepwise regression analysis using climatic factors show a high correlation coefficient compared to that without climatic factors. This research can be the precondition to do data fusion and then obtain CO2 near surface by fusing AIRS and GOSAT CO2 data.

9221-25, Session 3

The responses of vegetation water content (EWT) along a coastal region using remote sensing

Zhiqiang Gao, Yantai Institute of Coastal Zone Research (China)

Abstract: Monitoring of vegetation water not only aids in understanding the conditions for plant growth but also plays an indispensable role in assessing the risk of forest fire, monitoring of drought conditions and ecological security, and evaluating regional water resources. This paper retrieved the vegetation water content EWT (equivalent water thickness) information and the relevant parameters for the land surface from full-band TM remote sensing data. The effects of surface water heat flux and surface covering on the EWT were analyzed via studies of the regional land cover status and the combined EWT with land surface parameters.

9222-1, Session 1

Observing system simulation experiments to assess the potential impact of proposed satellite instruments on hurricane prediction

Robert M. Atlas, National Oceanic and Atmospheric Administration (United States); Thomas S. Pagano, Jet Propulsion Lab. (United States)

Observing System Simulation Experiments (OSSEs) are an important tool for evaluating the potential impact of proposed new observing systems, as well as for evaluating trade-offs in observing system design, and in developing and assessing improved methodology for assimilating new observations. Detailed OSSEs have been conducted at NASA/ GSFC and NOAA/AOML in collaboration with Simpson Weather Associates and operational data assimilation centers over the last three decades. These OSSEs determined correctly the quantitative potential for several proposed satellite observing systems to improve weather analysis and prediction prior to their launch, evaluated trade-offs in orbits, coverage and accuracy for space-based wind lidars, and were used in the development of the methodology that led to the first beneficial impacts of satellite surface winds on numerical weather prediction. New, OSSEs related to hurricane track and intensity prediction are being conducted at the present time as a collaboration between NOAA, NASA, Simpson Weather Associates, the University of Miami, and the Joint Center for Satellite Data Assimilation. The objectives of these OSSEs are to determine (1) the potential impact of unmanned aerial systems, (2) the relative impact of alternative concepts for space-based lidar winds, (3) the relative impact of alternative concepts for polar and geostationary hyperspectral sounders, and (4) the potential impact of geostationary microwave sounders and GNSS RO measurements of ocean surface wind. Results from these experiments will be presented at the conference.

9222-2, Session 1

Simulating satellite infrared sounding retrievals in support of Observing System Simulation Experiments (OSSEs)

Thomas S. Pagano, William S. Mathews, Frederick W. Irion, Jet Propulsion Lab. (United States)

Satellite infrared sounders including the Atmospheric Infrared Sounder (AIRS) on NASA's Earth Observing System Aqua satellite acquire temperature and water vapor profiles of Earth's atmosphere with global daily coverage and unprecedented vertical and horizontal resolution and accuracy from space. Simulating the data acquisition and retrieval process of sounders like AIRS applied to modeled atmospheric conditions (e.g. hurricanes) enables prediction of how well these systems should improve forecasts. Simulations using AIRS performed prior to development of the instrument predicted high forecast improvement with infrared sounders and were proven accurate with AIRS having among the highest impact of any observations to the operational forecast. The next generation of forecast models are expected to operate at an order of magnitude higher spatial resolution than those used for AIRS.

A new set of Observing System Simulation Experiments (OSSEs) are underway to assess the impact of higher spatial and temporal resolution sounding on hurricane forecast accuracy. To support these studies, we have developed an Infrared Sounding Instrument Retrieval Simulator (ISIRS). The ISIRS uses a satellite orbit track simulation to provide sample locations and footprint area of the infrared sounder configuration to be simulated over the region of interest. The OSSE nature run (simulated temperature and water vapor profiles and cloud properties) is sampled at the sounder locations and integrated over the sounder footprint area. The resulting averaged profiles are convolved with the AIRS averaging kernels using a linear retrieval methodology. The sampled and convolved profiles simulate the retrievals we can expect from the infrared sounder configuration under test. The results can be used in sensitivity and assimilation studies to assess the performance of these new sounders on forecast accuracy.

9222-3, Session 1

Tracking the evolution of spectral point spread functions on orbit

Kenneth F. Dymond, Scott A. Budzien, Andrew C. Nicholas, U.S. Naval Research Lab. (United States); Peter W. Walker II, Computational Physics, Inc. (United States)

The SSULI (Special Sensor Ultraviolet Limb Imager) is a limb-scanning far- and extreme-ultraviolet spectrograph designed to fly on the Defense Meteorological Satellite Program satellites. Three are currently in orbit, with a fourth slated to launch in 2014. Because the SSULI spectrograph is of moderate spectral resolution (~15-17 Å) and the Earth's EUV/ FUV airglow spectrum is fairly complex with emission features from atomic, molecular, and ionic species, deconvolution of the observed spectra requires good knowledge of individual spectral features in isolation. However, sensor aging renders much of the pre-flight line shape determination, especially of bright features, inaccurate early into the mission, requiring a means of determining these line shapes on orbit. A method of determining these line shapes from simpler, high altitude night airglow spectra to include all the features seen in the most complex daytime airglow spectra is presented. Additionally, because the SSULI detector is open to the space environment, line shapes for various background and ion noise features, which can be highly variable, are also modeled. The line-shape functions include models of the scattering wings, line core, photocathode migration/desensitization, and microchannel plate gain sag.

9222-4, Session 1

Advances in on-orbit EUV and FUV stellar calibrations by the Special Sensor Ultraviolet Limb Imager

Scott A. Budzien, U.S. Naval Research Lab. (United States); Peter W. Walker II, Computational Physics, Inc. (United States); Andrew C. Nicholas, U.S. Naval Research Lab. (United States)

The SSULI (Special Sensor Ultraviolet Limb Imager) is a limb-scanning far- and extreme-ultraviolet spectrometer designed to fly on the Defense Meteorological Satellite Program. Three are currently on orbit, with a fourth to launch in 2014. The sensor sensitivity is tracked through the mission life by taking advantage of fortuitous stellar apparitions which, over the course of several days, track across the sensor's field of view, allowing for not only the production of a sensitivity curve when compared against the known stellar spectra, but additionally pointing information and field-of-view information can be gleaned from comparing the star's expected and observed positions. Most notably, because the star's apparition traces across the field of view predictably in one axis, and randomly in another, multiple apparitions of these point sources can be used to map out the gain on the detector's entire surface, revealing the existence and extent of localized gain sags. Additionally, multiple, routinized, and scheduled calibrations can be used to track sensor behavior through the mission life, including effects like a detector scrub and probable loss of a photosensitive CsI coating. Results from the SSULI 002/DMSP F18 stellar calibrations are presented.

9222-5, Session 1

Differentiation of bacterial colonies and temporal growth patterns using hyperspectral imaging

Mehrube Mehrübeoglu, Gregory W. Buck, Daniel W. Livingston, Texas A&M Univ. Corpus Christi (United States)

The identification of pathogenic bacteria relies on various biochemical or DNA test methods for precise confirmation, which can be time consuming and costly when screening large amounts of unknown samples such as in the food and health industries. Hyperspectral imaging has the potential to identify unique spectral patterns obtained from a broadband light source which has interacted with and been diffusely reflected from the bacterial colonies; this process can then be used to identify different bacterial species and investigate growth-induced spectral changes.

The bacteria Pseudomonas fluorescens, Escherichia coli, Serratia marcescens, Salmonella enterica, Staphylococcus aureus, and Enterobacter aerogenes were grown on tryptic soy agar plates and imaged using a laboratory-based hyperspectral imaging system. Hyperspectral data cubes were acquired with a silicon based imaging sensor within the 400-1000 nm spectral range. Experiments were conducted right after incubation, 24 hours after incubation, and 96 hours after incubation at room temperature. The hyperspectral data were analyzed using ENVI and MATLAB software tools to determine variations across and within the bacterial species and over time.

Spectral signatures from bacterial colonies demonstrated repeatability and separability among five out of six species. Subtle changes in spectral signatures were observed across temporal test results within species at specific wavelengths, but were most prominent between spectral signatures for right after incubation and 96 hours after incubation. All bacteria were fully separable on scatter plots using combined features at three wavelengths. Future studies will determine if hyperspectral imaging can be used to differentiate bacteria under varying growth conditions and perturbations.

9222-6, Session 1

Modeling the expected performance of the REgoligth X-ray Imaging Spectrometer (REXIS)

Niraj K. Inamdar, Richard P. Binzel, Massachusetts Institute of Technology (United States); Jae Sub Hong, Branden T. Allen, Harvard-Smithsonian Ctr. for Astrophysics (United States); Rebecca A. Masterson, Massachusetts Institute of Technology (United States)

OSIRIS-REx is the third spacecraft in the NASA New Frontiers Program and is planned for launch in 2016. OSIRIS-REx will orbit the near-Earth asteroid 101955 Bennu, characterize it, and return a sample of the asteroid's regolith back to Earth. The Regolith X-ray Imaging Spectrometer (REXIS) is an instrument on OSIRIS-REx designed and built by students at MIT and Harvard. The purpose of REXIS is to collect and image sun-induced fluorescent X-rays emitted by Bennu, thereby providing spectroscopic information related to the chemical makeup of the asteroid regolith and the distribution of features over its surface.

Reflectance spectra suggest a CI or CM chondrite analogue meteorite class for Bennu. Its spectral similarities in different near-infrared bands to B-type asteroids 24 Themis and 2 Pallas raise the intriguing possibility that Bennu is a transitional object between the two. The discovery of water on the surface of 24 Themis and the primitive nature of carbonaceous chondrites in general provide additional scientific motivation for studying Bennu. A number of factors, however, will influence the generation, measurement, and interpretation of the X-ray spectra measured by REXIS. These include: the compositional nature and heterogeneity of Bennu, the time-variable solar state, X-ray detector characteristics, and geometric parameters for the observations.

In this paper, we will explore how these variables influence how precisely REXIS can measure Bennu's surface composition. By modeling the aforementioned factors, we place bounds on the expected performance of REXIS and its ability to ultimately place Bennu in an analogue meteorite class.

9222-7, Session 2

Stray light analysis of the focal plane filter stack on the Prototype HyspIRI-TIR (PHyTIR) instrument

William R. Johnson, Simon J. Hook, Marc C. Foote, Bruno M. Jau, Bjorn T. Eng, Jet Propulsion Lab. (United States)

The prototype hyspiri-tir (PHyTIR) instrument was developed under NASA's instrument incubator program and is now operational in the laboratory. The scan head uses state-of-the-art focal plane technology to rapidly acquire data from an eight inch telescope focused at infinite, reflective relay and continuously rotating scan mirror. A series of narrowband interference filters are placed in close proximity to the focal plane. Arrays of 256x16 Mercury Cadmium detectors are under each filter. The detectors have their long wave cutoff at 13.2?m. The filters serve to block out unwanted radiation from other spectral channels, hence forming a high performance multi-band imager with the use of the scanning mirror.

We show simulated and component level data of each filer. The results show adequate out-of-band blockage from incident visible to thermal infrared wavelengths. Other items are measured such bandwidth, shape and transmission. We then show system level data and compare. The filters are held at cryogenic temperatures. Each filter is designed with an assumed angle of incident which changes with respect to cross track field angle. The system level data shows very good performance. They also allow us to capture edge artifacts to show correlation with our stray light model.

9222-8, Session 2

Multislit optimized spectrometer: flight-like environment test results

William S. Good, Tim Valle, Peter Spuhler, Chuck Hardesty, Conor Staples, Ball Aerospace & Technologies Corp. (United States); Curtiss O. Davis, Nicholas B. Tufillaro, Oregon State Univ. (United States)

The NASA ESTO funded Multislit Optimized Spectrometer (MOS) Instrument Incubator Program will advance a spatial multiplexing spectrometer for coastal ocean remote sensing from laboratory demonstration to flight-like environment testing. The multiple slit design reduces the required telescope aperture leading to mass and volume reductions over conventional spectrometers when applied to the GEO-CAPE oceans mission. This paper discusses the performance and characterization of the MOS instrument from laboratory and thermal vacuum testing. It also discusses the current technology readiness level and possible future applications. Results of an ocean color data product simulation study using flight-like performance data from MOS will also be covered. The MOS instrument implementation for GEO-CAPE provides system benefits that may lead to measurable cost savings and reductions in risks while meeting its science objectives.

9222-9, Session 2

Field and laboratory test results demonstrating the error budget for the Climate Absolute Radiance and Refractivity Observatory

Kurtis J. Thome, Joel McCorkel, Brendan McAndrew, NASA Goddard Space Flight Ctr. (United States)

The Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission addresses the need to observe high-accuracy, long-term climate change trends and to use decadal change observations as a method to determine the accuracy of climate change. A CLARREO objective is to improve the accuracy of SI-traceable, absolute calibration at infrared and reflected solar wavelengths to reach on-orbit accuracies required to allow climate change observations to survive data gaps and observe climate change at the limit of natural variability. Such an effort will also demonstrate NIST approaches for use in future spaceborne instruments.

The current work describes a set of laboratory and field measurements with the Solar, Lunar for Absolute Reflectance Imaging Spectroradiometer (SOLARIS) which is the calibration demonstration system (CDS) for the reflected solar portion of CLARREO. SOLARIS allows testing and evaluation of calibration approaches, alternate design and/or implementation approaches and components for the CLARREO mission. SOLARIS also provides a test-bed for detector technologies, non-linearity determination and uncertainties, and application of future technology developments and suggested spacecraft instrument design modifications. Past work has provided background for an SI-traceable error budget for reflectance retrieval using solar irradiance as a reference and methods for laboratory-based, calibration suitable for climate-quality data collections. Results of laboratory calibration measurements are provided to demonstrate key assumptions about instrument behavior that are needed to achieve CLARREO's climate measurement requirements. Results from field measurements and reflectance retrievals using direct solar views are also shown giving confidence in the error budget for the CLARREO reflectance retrieval.

9222-10, Session 3

Lessons and results from 30 years of imaging spectroscopy *(Invited Paper)*

Robert O. Green, Jet Propulsion Lab. (United States)

Spectroscopy is a powerful analytical method used to derive compositional and process information remotely through the interaction of light with matter. Fraunhofer first used spectroscopy to discover the composition of the solar atmosphere in the 1800's. Hubble used spectroscopy to discover the expanding nature of our universe.

In the late 1970's with advances in detector, optical, and electronic technologies, instruments that measured spectra for each point in an image became feasible. The Airborne Imaging Spectrometer was proposed in 1979 and first few in 1982, making scientific discoveries in the first year. Based on this success, the more capable Airborne Visible-Infrared Imaging Spectrometer was proposed in 1983 and first flew in 1986. This instrument has flown in every year through 2013. In the intervening years, imaging spectrometers have flown to Jupiter, Saturn, Mars, the Moon, other solar system objects and orbited Earth. This paper presents key lessons learned and science discoveries as well as prospects for the future of imaging spectroscopy that enables remote measurement from the microscopic scale to exoplanet distances.

9222-11, Session 3

Design of the Compact Wide Swath Imaging Spectrometer (CWIS)

Byron Van Gorp, Pantazis Mouroulis, Robert O. Green, Daniel W. Wilson, Jet Propulsion Lab. (United States)

The Compact Wide Swath Imaging Spectrometer (CWIS) is an imaging spectrometer for the solar reflected spectrum (380-2500 nm) with wide swath (1600 elements), fast optical speed (F/1.8), and high uniformity ($\geq$95%). A compact Dyson form allows the spectrometer to be one tenth the volume and mass of the equivalent Offner-type instrument with 2.5 X the swath and 2X the signal-to-noise ratio. Optical design, stray light modeling and opto-mechanical layout of the design are discussed.

9222-12, Session 3

Design of a CubeSat-compatible imaging spectrometer

Pantazis Mouroulis, Byron Van Gorp, Robert O. Green, Daniel W. Wilson, Jet Propulsion Lab. (United States)

The CubeSat Imaging Spectrometer (CubIS) has been designed to address localized coastal applications and can satisfy the stringent requirements of those applications by maximizing the light collection and minimizing the polarization sensitivity, operating in the spectral range 350-1700 nm. A compact Dyson form allows the spectrometer, reflective telescope (100mm, F/1.8, 10o linear FOV), and on-board calibrator to fit in a 4U volume. The stray light considerations that drive the design are discussed.

9222-13, Session 3

Wide-field imaging spectrometer for the Hyperspectral Infrared Imager (HyspIRI) mission

Holly A. Bender, Pantazis Mouroulis, Robert O. Green, Daniel W. Wilson, Ronald J. Korniski, Jet Propulsion Lab. (United States)

The Hyperspectral Infrared Imager (HyspIRI) is designed to study the world's ecosystems from low Earth orbit, providing critical information on vegetation type and health, and on natural disasters such as volcanoes, wildfires and drought. We present an optical design that satisfies the HyspIRI requirements for a visible and short-wave infrared imaging spectrometer. We also discuss tolerancing and alignment techniques required in order to achieve the stringent HyspIRI specifications.

9222-14, Session 3

Remote plume detection with the Hyperspectral Thermal Emission Spectrometer (HyTES)

William R. Johnson, Simon J. Hook, Glynn Hulley, Jonathan Mihaly, Jet Propulsion Lab. (United States)

The hyperspectral thermal emission spectrometer was developed under NASA's instrument incubator program and has now completed three deployments. The scan head uses a state-of-the-art Dyson spectrometer cooled to 100K coupled to a quantum well infrared photodetector array held at 40K. The combination allows for 256 spectral channels between 7.5?m and 12?m with 512 cross track spatial pixels. Spectral features for many interesting gases fall within the instrument passband.

We first review the pre-flight calibration and validation process for HyTES using a suite of instrumentation. This includes a smile measurement at two wavelengths (8.18 and 10.6mm) as well as a concentration determination using large aperture gas cells. We then show positive gas plume detection at ranges >1000m for various cases: Ammonia gas detection from Salton Sea fumaroles, Methane detection from staged releases points in Wyoming as well as naturally occurring methane hot spots off the coast of Santa Barbara.

9222-15, Session 4

Radiometric sensitivity contrast metrics for hyperspectral remote sensors

John F. Silny, Louis Zellinger, Raytheon Co. (United States)

This paper discusses the calculation, interpretation, and implications of various radiometric sensitivity metrics for Earth-observing hyperspectral imaging (HSI) sensors. The most commonly used sensor performance metric is signal-to-noise ratio (SNR), from which additional noise equivalent quantities can be computed, including: noise equivalent spectral radiance (NESR), noise equivalent delta reflectance (NEΔρ), noise equivalent delta emittance (NEΔε) and noise equivalent delta temperature (NEΔT). These metrics are calculated from an at-aperture radiance (typically generated by MODTRAN) that includes both target radiance and atmospheric path radiance. Unfortunately, typical calculations treat the entire at-aperture radiance as the desired signal, even when the target radiance is only a fraction of the total (such as when sensing through a long or optically dense atmospheric path). To overcome this limitation, an augmented set of metrics based on contrast signal-to-noise ratio (CNSR) is developed, including their noise equivalent counterparts (CNESR, CNEΔρ, CNEΔε, and CNEΔT). These contrast metrics better quantify sensor performance in an operational environment that includes remote sensing through the atmosphere.

9222-16, Session 4

Modeling effects of the bidirectional reflectance distribution function on remote sensing in the LWIR

Samuel D. Butler, Michael A. Marciniak, Air Force Institute of Technology (United States); Joseph Meola, Air Force Research Lab. (United States)

In the long wave infrared (LWIR), often one assumes a scene does not contain solar reflection. This assumption is valid under the premise of a Lambertian reflector, as is often assumed in imaging spectrometry to determine the content of a pixel. To begin analysis of directional reflection effects on a scene, a simple hemispherical model is developed. In this model, diffuse downwelling radiation is modeled as a blackbody at 250 K, with an object of interest in the scene at 300 K. The solar disk is modeled as a blackbody at 5800 K. Then, several notional bidirectional reflectance distribution functions (BRDFs) with directional-hemispherical reflectances (DHRs) of 0.9 and 0.5 are assigned to the material in the scene. The directional dependence of the BRDF is taken from the densely-measured Mitsubishi Electronics Research Lab (MERL) database to use measured BRDF data rather than a model generated from a minimal set of BRDF measurements. The BRDF is scaled to the appropriate maximum DHR. The relative contributions of diffuse downwelling, solar, and self-emissive radiance to the total radiance are computed for all observer and solar angles at 8 microns. The model result is that, for certain non-Lambertian BRDFs, it is possible to orient an object in the scene in such a manner as to make the solar radiance not negligible in LWIR. A tower test may be conducted to validate this modeling. This suggests BRDFs should be included in hyperspectral remote sensing even in the LWIR to properly analyze scenes with non-negligible solar reflectance.

9222-17, Session 4

Geophysical applications of spectral deconvolution using the Richardson-Lucy algorithm

Kenneth F. Dymond, Scott A. Budzien, Andrew C. Nicholas, U.S. Naval Research Lab. (United States)

Many geophysical applications require the deconvolution of spectra to derive the observed line intensities. These spectra are commonly deconvolved using techniques like Multiple Linear Regression (MLR) under the assumption that the measurements are normally distributed random variables. When the signals are strong the measurements are normally distributed the MLR technique can be used and will produce accurate results, but when the signal intensities are weak or are shot-noise limited and Poisson statistics apply MLR can produce undesirable results such as negative, non-physical count rates and fits to the spectra. The Richardson-Lucy algorithm is an iterative technique that inherently includes Poisson statistics and non-negativity constraints naturally. We show that this algorithm can be used to produce fast, accurate deconvolution of spectra under conditions where Poisson statistics hold while maintaining the non-negativity constraints that ensure physicality of the solutions for geophysical applications.

9222-18, Session 4

Using kernel-based and single-scattering albedo approaches for generalized spectral mixture analysis of hyperspectral imagery

Robert S. Rand, National Geospatial-Intelligence Agency (United States); Ronald G. Resmini, The MITRE Corp. (United States)

Spectral mixing can occur in a number of different ways, which may be linear or non-linear. Perhaps the pixel size of a sensor is just too large so many pixels contain patches of different materials within them resulting in linear mixing of the materials. However, there are more complex situations, such as scattering that occurs in mixtures of vegetation and soil, or intimate mixing of granular materials like soils. Such multiple scattering and microscopic mixtures within pixels have varying degrees of non-linearity. Often enough, scenes may contain cases of both linear and non-linear mixing on a pixel-by-pixel basis. This study compares two approaches for use as a generalized method for un-mixing pixels in a scene that may be linear or non-linear. The first is a kernel-based fully-constrained method for spectral unmixing, which uses a kernel that seeks to capture the linear behavior of albedo in non-linear mixtures of materials. The second method directly converts reflectance to single-scattering albedo (SSA) according to Hapke theory assuming bidirectional scattering at nadir look angles and uses a constrained linear model on the computed albedo values. Multiple scenes of hyperspectral imagery calibrated to reflectance are used to validate the methods.

9222-19, Session 4

Spatial-spectral metric learning for hyperspectral remote sensing image classification

Jiangtao Peng, Hubei Univ. (China); Yicong Zhou, C. L. Philip Chen, Univ. of Macau (China)

Metric learning aims to learn a distance metric from the given samples, which is very useful in many distance or similarity-based pattern recognition tasks. In this paper, we propose a spatial-spectral metric learning (SSML) framework for hyperspectral image (HSI) classification. Rather than using only spectral characteristics as in traditional metric learning methods, SSML learns the metric by considering both the spectral features and spatial neighboring pixel relations. In detail, we first perform the local pixel neighborhood preserving embedding (LPNPE) to reduce the dimensionality and meanwhile to preserve the local similarity structure of HSI. Then, we represent each HSI pixel as spectral vector and spatial vector simultaneously, where the spatial vector is extracted from the spatial local pixel neighborhood, i.e., the mean or standard deviation of neighboring pixels. Based on the spectral and spatial features, we can learn a spectral and spatial distance metric, separately. Finally, the combination of the spectral and spatial metric yields a spatial-spectral distance metric, which is followed by a nearest neighbor (NN) classifier for HSI classification. In learning the distance metric, we generate positive and negative sample pairs from the K

nearest neighbors in training samples, and learn a Mahalanobis distance metric by performing the support vector machine (SVM) classification on the covariance matrix of the generated sample pairs. The proposed SSML method is compared with the representative large margin nearest neighbor (LMNN) metric learning method, NN, SVM, SVM with composite kernel (SVM-CK). Experimental results on benchmark HSI datasets show the superiority of the proposed SSML.

9222-20, Session 4

Monte-Carlo radiative transfer simulation of bottom reflectance in optically shallow water columns

Abdoul Nasser Ibrahim, Jianhua Gong, Institute of Remote Sensing and Digital Earth (China); Masahiro Murakami, Kochi Univ. of Technology (Japan)

Solar irradiance reflected by the bottom of optically shallow waters makes a significant or dominant contribution to water-leaving radiance received at sensor. A Monte-Carlo radiative transfer simulation algorithm is herein proposed for quantitative estimation of bottom reflectance. The method statistically simulates the distribution of solar irradiance within the water column-bottom system along the propagation direction. In the process, light photons undergo scattering events affecting their energy levels through particle absorption. In addition, their propagation directions and their path lengths follow random processes taking respectively the phase function of the particles and the extinction coefficient of inhomogeneous media as probability distributions. In the model development, the down-welling and the up-welling radiance components were first parameterized. Then, by idealizing the bottom as a perfectly lambertian surface, the boundary condition represented by the Bidirectional Reflectance Distribution Function (BDRF) was used to couple the resulting equations. Basic data for the simulation algorithm consist of (i) hyperspectral remote sensing Rrs(λ) data of the experimental water columns measured in the Laboratory under controlled conditions using a hyperspectral FieldSpec Pro ASD spectro-radiometer; (ii) absorption a(λ) spectra; and (iii) attenuation c(λ) spectra of experimental columns both computed from the Rrs(λ) data. The proposed method computes the whole visible light spectrum as opposed to single wavelength calculations encountered in traditional methods. In addition, it can describe physical phenomena like scattering, absorption, and bottom reflection. The algorithm shows clear differences between turbid water columns with limited bottom reflectance effect, and clear water columns where the bottom contribution was significant.

9222-21, Session PMon

LITES and GROUP-C: multi-sensor ionospheric imaging from the ISS

Andrew W. Stephan, Scott A. Budzien, U.S. Naval Research Lab. (United States); Supriya Chakrabarti, Timothy A. Cook, Univ. of Massachusetts Lowell (United States); Steven P. Powell, Mark L. Psiaki, Cornell Univ. (United States)

The Limb-imaging Ionospheric and Thermospheric Extreme-ultraviolet Spectrograph (LITES) and GPS Radio Occultation and Ultraviolet Photometry-Colocated (GROUP-C) experiments are being considered for flight aboard the Space Test Program Houston 5 (STP-H5) experiment pallet to the International Space Station (ISS). LITES is a compact imaging spectrograph that makes one-dimensional images of atmospheric and ionospheric ultraviolet (60-140 nm) airglow above the limb of the Earth. The LITES optical design is advantageous in that it uses a toroidal grating as its lone optical surface to create these high-sensitivity images without the need for any moving parts. GROUP-C consists of two instruments: a nadir-viewing ultraviolet photometer that measures nighttime ionospheric airglow at 135.6 nm with unprecedented sensitivity, and a GPS receiver that measures ionospheric electron content and scintillation with the assistance of a novel antenna array designed for multipath mitigation. By flying together, these two experiments present an opportunity to create an ionospheric observatory aboard the ISS that would provide new capability to study low- and mid-latitude ionospheric structures on a global scale. This paper will discuss the design and implementation of the LITES and GROUP-C experiments on the STP-H5 payload, and the challenges and opportunities associated with the tomographic techniques that will combine for the first time high-sensitivity in-track photometry with vertical spectrographic imagery of ionospheric airglow to create high-fidelity images of ionospheric structures.

9222-22, Session PMon

Preflight calibration of the Special Sensor Ultraviolet Limb Imager

Peter W. Walker II, Computational Physics, Inc. (United States); Andrew C. Nicholas, Andrew W. Stephan, Scott A. Budzien, U.S. Naval Research Lab. (United States)

The SSULI (Special Sensor Ultraviolet Limb Imager) is a limb-scanning far- and extreme-ultraviolet spectrometer designed to fly on the Defense Meteorological Satellite Program. Three are currently on orbit, with a fourth to launch in 2014. The SSULI detector consists of an unwindowed microchannel plate stack, permitting the observation of wavelengths shorter than 105 nm. Because the detector is open, it is especially susceptible to interaction with the spacecraft environment, mainly with ions and neutral gas that enter the instrument assembly. In preparation for delivery and integration of the SSULI 005 sensor to the DMSP F19 satellite, two final pre-flight calibrations were performed. In the course of the calibration analyses, it was observed that the sensor background directly correlated to the gas being used in the unwindowed arc lamp to stimulate test emissions. Specifically, N_2 and to a lesser degree O_2 were found to produce significant additional backgrounds at the edges of the detector's active area, while H_2, Xe, and Ar produced backgrounds indistinguishable from a dark count. When the lamp was windowed, the enhanced backgrounds from N_2 and O_2 were no longer observed. A new method of producing a gas-specific background was developed by combining multiple scaled emissions from the same gas and masking the portion of the detector receiving photons. These new backgrounds assisted the fitting of weak calibration features near the edges of the detector's passband. A geometric explanation of the shape of the background is also discussed.

9222-23, Session PMon

Random projection-based dimensionality reduction method for hyperspectral target detection

Weiyi Feng, Nanjing Univ. of Science and Technology (China)

Dimensionality reduction is a frequent preprocessing step in hyperspectral image analysis. High-dimensional data will cause the issue of the "curse of dimensionality" in the applications of hyperspectral imagery. In this paper, a dimensionality reduction method of hyperspectral images based on random projection (RP) for target detection was investigated. In the application areas of hyperspectral imagery, e.g. target detection, the high dimensionality of the hyperspectral data would lead to burdensome computations. Random projection is attractive in this area because it is data independent and computationally more efficient than other widely-used hyperspectral dimensionality-reduction methods, such as Principal Component Analysis (PCA) or the maximum-noise-fraction (MNF) transform. In RP, the original high-dimensional data is projected onto a low dimensional subspace using a random matrix, which is very simple. Theoretical and experimental results indicated that random projections preserved the structure of the original high-dimensional data quite well without introducing significant distortion. In the experiments, Constrained Energy Minimization (CEM) was adopted as the target detector and a RP-based CEM method for hyperspectral target detection was implemented to reveal that random projections might be a good alternative as a dimensionality reduction tool of hyperspectral images to yield improved target detection with higher detection accuracy and lower computation time than other methods.

9223-1, Session 1

Improvements in weather forecasting and disaster monitoring resulting from the STORM geosynchronous infrared sounder *(Invited Paper)*

Allen H.-L. Huang, Univ. of Wisconsin-Madison (United States)

No abstract available

9223-2, Session 1

Satellite data fusion and information retrieval with ground-based sensor networks for monitoring ecosystem evolution *(Invited Paper)*

Ni-Bin Chang, Univ. of Central Florida (United States)

The frequencies of occurrence of Harmful Algal Bloom (HAB) events in Lake Erie and elsewhere may be tied to an integrated response of climate change impact (temperature change) and anthropogenic disturbance (changing nutrient cycling). These conditions result in the formation of algal blooms, some of which are toxic due to the presence of Microcystis (a cyanobacteria), which produces the hepatotoxin microcystin. The toxin threatens human health and the ecosystem, and it is a concern for water treatment plants using the lake water as a tap water source. This paper demonstrates the prototype of a near real-time early warning system using Integrated Data Fusion and Mining (IDFM) techniques to determine spatiotemporal microcystin concentrations and by measuring the surface reflectance of the water body using satellite sensors. The fine spatial resolution of Landsat is fused with the high temporal resolution of the Moderate Resolution Imaging Spectroradiometer to create a synthetic image possessing algorithm producing images with both high temporal and spatial resolution. As a demonstration, the spatiotemporal distribution of microcystin within western Lake Erie is reconstructed using the band data from the fused products and applied machine-learning techniques. Analysis of the results through statistical indices confirmed that the genetic programming model has potential to accurately estimating microcystin concentrations in the lake, which is better than all current 2-band and 3-band models and other computational intelligence models. To provide synchronous in-situ Microcystis measurements by an automatic way, an electrochemical sensor embedded in robotic fishes in the future may provide a good means for instantaneous model recalibration over the period of time. This will enable us to create an all-weather early warning system for water quality monitoring and ecosystem management to promote urban and coastal sustainability.

9223-3, Session 1

Persistent observations of the Arctic from a highly elliptical orbit using multispectral, wide field of view day-night imagers *(Invited Paper)*

Jeffery J. Puschell, Raytheon Space & Airborne Systems (United States); David B. Johnson, National Ctr. for Atmospheric Research (United States); Steven D. Miller, Colorado State Univ. (United States)

No abstract available

9223-4, Session 1

VIIRS reflective solar bands on-orbit calibration coefficient performance using imagery and moderate band intercomparisons

David I. Moyer, Nicholas R. Vandermierden, Kameron Rausch, Frank De Luccia, The Aerospace Corp. (United States)

A primary sensor on-board the Suomi-National Polar-orbiting Partnership (SNPP) spacecraft, the Visible-Infrared Imaging Radiometer Suite (VIIRS) has 22 bands: 7 thermal emissive bands (TEBs), 14 reflective solar bands (RSBs) and a Day Night Band (DNB). The RSBs cover the spectral wavelengths between 0.412 to 2.25 µm and have three (I1-I3) 371m and eleven (M1-M11) 742m spatial resolution bands. A VIIRS Key Performance Parameter (KPP) is the Ocean Color/Chlorophyll (OCC) which uses moderate bands M1 (0.412µm) thru M7's (0.865 µm) calibrated Science Data Records (SDRs). The RSB SDRs rely on prelaunch calibration coefficients which use a quadratic algorithm to convert the detector's response to calibrated radiance. This paper will evaluate the performance of these prelaunch calibration coefficients using SDR comparisons between bands with the same spectral characteristics: I2 with M7 (0.865 µm) and I3 with M10 (1.610 µm). Changes to the prelaunch calibration coefficient's offset term c0 to improve the SDR's performance at low radiance levels and how they affect OCC will also be discussed.

9223-5, Session 1

Impact of changes in VIIRS solar reflective band sensitivity due to aging on environmental data record performance

Jeffery J. Puschell, Vijay Murgai, Raytheon Space & Airborne Systems (United States)

No abstract available

9223-6, Session 2

Uncooled emissive infrared imager for a CubeSat *(Invited Paper)*

Jeffery J. Puschell, Raytheon Space & Airborne Systems (United States); Paolo Masini, Raytheon Co. (United States)

No abstract available

9223-7, Session 2

Calibration of a system to collect visible-light polarization data for classification of geosynchronous satellites

Andy Speicher, Mohammad A. Matin, Univ. of Denver (United States); Roger Tippets, Francis K. Chun, U.S. Air Force Academy (United States)

In order to protect critical military and commercial space assets, the United States Space Surveillance Network must have the ability to positively identify and characterize all space objects. Unfortunately, positive identification and characterization of space objects is a manual and labor intensive process today since even large telescopes cannot provide resolved images of most space objects.

The objective of this study was to calibrate a system to exploit the optical signature of unresolved geosynchronous satellite images by collecting polarization data in the visible wavelengths for the purpose of revealing discriminating features. These features may lead to positive identification or classification of each satellite. The system was calibrated and preliminary data was collected to validate the system performance. Different collection geometries were used to evaluate data that may be used to characterize the contribution of solar arrays, thermal control materials, antennas, and satellite bus at various solar phase angles. As space objects age due to the space environment, their polarization signature may change enough to allow discrimination of identical satellites launched at different times.

This instrumentation is part of the new United States Air Force Academy (USAFA) Department of Physics Falcon Telescope Network (FTN). The system used for this experiment consists of one 20-inch Ritchey-Chretien telescope and a dual focal plane system fed with a polarizing beam splitter. This study calibrated the system and collected preliminary polarization data on five geosynchronous satellites that were built by different manufacturers and launched several years apart.

9223-9, Session 3

2 micron pulsed remote sensing of atmospheric carbon dioxide *(Invited Paper)*

Jirong Yu, Mulugeta Petros, Upendra N. Singh, NASA Langley Research Ctr. (United States)

A 2-micron pulsed direct detection Integrated Path Differential Absorption (IPDA) lidar is developed for atmospheric CO2 measurements. Development of this lidar heavily leverages the 2-micron laser technologies developed in LaRC over the last decade. The high pulse energy IPDA lidar operating at CO2 2-micron absorption band provides an alternate approach to measure CO2 concentrations with significant advantages. It provides high-precision measurement capability by unambiguously eliminating contamination from aerosols and clouds that can bias the IPDA measurement.

This lidar technology enables an airborne capability to perform a first proof of principle demonstration of airborne direct detection CO2 measurements. The 2-micron transmitter provides 100mJ at 10Hz with double pulse format specifically designed for DIAL/IPDA instrument. This paper will describe the design of the airborne 2-micron pulsed IPDA lidar system; the lidar operation parameters; the wavelength pair selection; laser transmitter energy, pulse rate, beam divergence, double pulse generation and accurate frequency control; detector characterization; telescope design; lidar structure design; and lidar signal to noise ratio estimation. The ground test and first airborne lidar results will be presented.

9223-10, Session 3

Control architecture for an adaptive electronically steerable flash lidar and associated instruments

Lyle Ruppert, Jeremy Craner, Timothy R. Harris, Ball Aerospace & Technologies Corp. (United States)

An Electronically Steerable Flash Lidar (ESFL), developed by Ball Aerospace & Technologies Corporation, allows real-time adaptive of configuration and data-collection strategy based on recent or concurrent observations and changing situations. This paper reviews at a high level some of the algorithms and control architecture built into ESFL. Using ESFL as an example, it also discusses more generally the merits and utility such adaptable instruments in Earth-system studies.

9223-11, Session 3

Improving accuracy of pulsed-laser range finding based on differential optical path

Jie Cao, Hao Qun, Jiaxing Mu, Beijing Institute of Technology (China)

A pulsed-laser range finding based on differential optical-path is proposed. The peak detection is transformed in to zero-crossing point, which result into suppressing background noise and improve range accuracy. The mathematical models of differential echo are developed and verified, and the effects of difference of receivers, range and tilted angle of target are discussed. Based on the method, experiments are carried out and conclusions are obtained. (1) Compared with traditional range finder i.e. single receiver, background noise can be suppressed effectively. (2) Peak detection of traditional method is transform into zero-crossing point, which avoid the effects on echo detecting from pulsed-width broadening. (3) Under the same range condition, the range accuracy is improved twice as much as the traditional method.

9223-12, Session 3

An instrument for measurement of spontaneous Rayleigh-Brillouin scattering profiles in atomic and molecular gases

Xingdao He, Jing Feng, Tao Wu, Ruxiao Xia, Nanchang Hangkong Univ. (China)

An instrument for measurement of spontaneous Rayleigh-Brillouin scattering line profiles in atomic and molecular gases has been developed. A high-power continuous-wave laser at 532nm with narrow bandwidth was employed.The beam emitted by the laser was focused into a gas scattering cell. The scattering light was collected at an angle of 90° from injection laser beam. A scannable Fabry-Perot analyzer with FSR of 7.5GHz probed the Rayleigh-Brillouin profiles. The spontaneous Rayleigh-Brillouin scattering profiles in atomic and molecular gases at pressures ranging from 1 to 8 bar were measured and compared to Tenti S6 model. The deviation between experimental results and Tenti S6 model were analyzed.

9223-13, Session 4

Integrated ocean observing system *(Invited Paper)*

Philip E. Ardanuy, Raytheon Intelligence & Information Systems (United States)

No abstract available

9223-14, Session 4

Pattern recognition applied to infrared images for early alerts in fog

Mario Marchetti, Vincent Boucher, Portal Cerema (France); Jean Dumoulin, Aurélien Cord, Institut Francais des Sciences et Technologies des Transports de l'amenagement et des Reseaux (France)

Fog conditions are the cause of severe car accidents in western countries because of the poor induced visibility. Its forecast and intensity are still very difficult for weather services. Infrared cameras allows to detect objects and to identify objects in fog while visibility is too low for eye detection. Over the past years, the implementation of cost effective infrared cameras on some vehicles has enabled such detection. On the

other hand pattern recognition algorithms based on Canny filters and Hough transformation are a common tool applied to images. Based on these facts, they were developed and investigated during a joint research program between IFSTTAR and CEREMA to infrared images obtained in a fog tunnel for two different water droplets granular size and distribution. Infrared images were obtained with a FLIR S65 camera operating in the 7-14 µm band, at a 1Hz frequency, with a 24° lens, during the fog natural dissipation. Infrared data was converted into grey level images for the implementation of pattern recognition algorithms, specifically on road signs which shape is usually associated to a specific meaning (circular for a speed limit, triangle for an alert, …). It has been shown that road signs were detected early enough in images, with respect to images in the visible spectrum, to trigger useful alerts for drivers.

9223-15, Session 4

Appreciation of the traffic effects on the road surface temperature by infrared thermography

Abderrahmen Khalifa, Mario Marchetti, Portal Cerema (France); Michel Buès, Univ. de Lorraine (France)

Road surface temperature forecast is a key component of winter maintenance strategy in many developed countries. Numerical tools exist to help road managers to organize services and consequently triggering de-icing operations. Forecasting strategies have been commonplace since the 1980s, and are often based on numerical models. Traffic is one of the influencing parameters, specifically in urban areas. This work was undertaken so as to evaluate to which extent an accurate description of traffic might improve numerical model dedicated to road surface temperature forecasting. Two sets of experiments were run to detect and to quantify traffic effects on RST. The first set consisted in driving above an infrared radiometer (Keller PS12 AF1, -30°C to 70°C temperature range, 0.7°C resolution), a pyrgeometer and other atmospheric probes to measure the radiative contribution of a passing vehicle at various speeds (10 to 60 km/h). In the second set, an infrared camera was installed on a vehicle in an urban traffic flow. The FLIR S65 infrared camera was mounted on the roof and focused the pavement right behind the vehicle ahead, both having the same speed. Thermal images were collected in their native format, roughly every 2 seconds. RST was also measured with the same radiometer quoted before. Infrared thermography indicated a fleeting contribution of traffic to RST. The temperature increase in circulated areas, with respect to uncirculated ones, does not last according to collected measurements. Measurements with atmospheric and radiometric probes provided elements to properly take into account traffic in TEB numerical model and appreciate its contribution.

9223-16, Session 4

Monitoring system for 3D and 4D applications using smart cameras

Jinwoo Park, Hohyun Jung, Minseok Kim, ChulUong Choi, Yeon Yeu, Pukyong National Univ. (Korea, Republic of)

Recently, unusual climate changes have world widely spurred the demand for environmental monitoring systems to prepare for these natural disasters, as well as to aid in recovery procedures. Conventional monitoring systems require power supplies and communication lines, which are not cost effective, particularly for short-term observation. Information technology advances are allowing conventional surveillance systems to be combined with mobile communication technologies with emerging smart cameras. This paper proposes a monitoring system using smart camera technology. A monitoring housing is designed to protect a camera from various weather conditions and to provide the camera for power generated from solar panel. A smart camera is installed in the monitoring housing. The smart camera is operated and controlled through an Android application. We discuss the dependence of interior orientation parameters on the type of calibration target sheets, because the cameras are non-metric ones. At last the accuracy of a three-dimensional monitoring system is evaluated using a digital surface model (DSM). The proposed system was then tested against a DSM created from ground control points determined by global positioning systems (GPSs) and light detection and ranging data. The standard deviation of the differences between DSMs are less than 0.12 m. Therefore the monitoring system is appropriate for extracting the information of objects' position and deformation as well as monitoring them. This monitoring system is able to analyze the trend and amount of disaster.

9223-17, Session 4

A hybrid algorithm for robust acoustic source localization in noisy and reverberant environments

Ramesh Rajagopalan, Timothy Dessonville, Univ. of St. Thomas (United States)

Acoustic source localization using microphone arrays is widely used in videoconferencing and surveillance systems. However, it still remains a challenging task to develop efficient algorithms for accurate estimation of source location using distributed data processing. In this work, we propose a new algorithm for efficient localization of a speaker in noisy and reverberant environments such as videoconferencing. A large number of source localization algorithms have been proposed in the literature with varying degrees of accuracy and complexity. Among these, the generalized cross correlation based phase transform method (GCC-PHAT) which estimates the time delay of arrival (TDOA) from microphones is the most widely used. In this method, closed form solution for the source location can be determined using the TDOAs from an array of at least four microphones. However, GCC-PHAT has been found to perform poorly in the presence of noise and reverberation which are prominent in real world systems. To address these challenges, we propose a hybrid algorithm that combines GCC-PHAT and Tabu search to obtain a robust and accurate estimate of the speaker location. The Tabu Search algorithm iteratively improves the TDOA estimate of GCC-PHAT by examining the neighboring solutions until a convergence in the TDOA value is obtained. Experiments were performed based on real world data recorded from a meeting room in the presence of noise. Our results demonstrate that the proposed hybrid algorithm outperforms GCC-PHAT especially when the noise level is high. This shows the robustness of the proposed algorithm in noisy and realistic videoconferencing systems.

9223-8, Session PMon

Monitoring LUCC from outer space in high spatial resolution based on objected-oriented method

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Land-Use is the true reflection of land surface conditions, which is one of the most important input parameters for the simulation of biogeochemical cycle, and has very important significance for the research of earth system science. Unfortunately, human activities cause Land-Cover Changes every day, therefore, it is necessary to monitor Land-Use and Land-Cover Changes (LUCC) by using new technologies and methods. This article mainly introduced the Land-Use, in 2000, 2005, and 2010, mapping process at the scale of 1:250000 in Zhejiang province, China, based one of supervised classification methods which combined object-oriented method and binary decision tree. The data used mainly is Landsat TM, and the mainly technique is remote sensing. In the article, we first took an overview of the study area and the data used for

Land-Use mapping. After that, we introduced the binary flow chart of Land-Use mapping based on object-oriented method, and the means which are used for features selection and threshold determination during the processes of classification. Thirdly, through the confusion matrix, we verified the accuracy of Land-Use mapping introduced in this article. Finally, we analyzed the Land-Cover Changes in Zhejiang Province from 2000 to 2005 and 2005 to 2010. The results of the research show that Land-Use mapping in Zhejiang province with high precision at the scale of 1:250000 can be realized by the method of combining object-oriented method and binary decision tree, and total accuracy and Kappa coefficient in 2010 is 0.8928 and 0.8752 respectively. Beyond that, we got that Land-Cover Changes from 2000 to 2005 and 2005 to 2010 are very apparent, especially the expansion of building zones from cultivated land.

9223-18, Session PMon

An optical positioning sensor by combining optical projection and a virtual camera model

Benrui Zheng, Yue Dong, Brigid A. Mullany, Edward P. Morse, Angela Davies, The Univ. of North Carolina at Charlotte (United States)

No Abstract Available

9223-19, Session PMon

Interferometric verification on focal plate flatness of Earth-observing Cassegrain Telescope

Ho-Lin Tsay, Ting-Ming Huang, Chia-Yen Chan, Instrument Technology Research Ctr. (Taiwan)

Field curvature in optical system is an optical aberration related to focal point position deviation rather than size or shape of point spread function. Value of deviation to focal plane is dependent on the lens type and optical design. For example, comparing to version used in astronomy, a Cassegrain telescope used in earth-observing application has a relative large focal plane and usually equipped with an additional set of corrector lens as a part of design to reduce its field curvature deviation in the focal plane. A good optical design minimizes this deviation to several micrometers throughout whole range of focal plane. To prevent case that focalization becomes impossible, focus deviation should be check before performing focalization between telescope and its imaging sensor. To get this deviation, we extract position data for several field angles to get the map of deviation. We propose a method to used WFE measuring equipment to get deviation map after optical alignment in case that telescope is not a telecentric design.

SETUP

An AC flat mounted on electronic 2-axis tilt shift. Interferometer is mounted on five axes stage with two rotation directions and three translation directions. Telescope is mounted on a gimbal providing horizontal rotation and tilt adjustment.

TELECENTRIC

In case that optical design is telecentric, deviation measurement is straightforward. For non-telecentric design as our telescope, interferometer module needs additional rotation to get the best focus point of every field point off axis. This arm of rotation should be measured before measuring best focus of field points.

DISCUSSION

Case of existing significant astigmatism is discussed.

9223-20, Session PMon

Development of a fiber-optic temperature sensor based on aqueous solution of sodium chloride

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In this study, a fiber optic temperature sensor was developed using an aqueous solution of sodium chloride (NaCl) and an optical time-domain reflectrometer (OTDR) to measure temperature at a long distance. We obtained the response time and the relationship between the optical power of the proposed temperature sensor and the temperature of water.

9223-21, Session PMon

Radio occultation based on BD satellite navigation

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with the development of GNSS systems, it has become a tendency that radio occultation is used to sense the Earth's atmosphere. By this means, the moisture, temperature, pressure, and total electron content can be derived. Based on the sensing results, more complicated models for atmosphere might come into being. Meteorology well benefits from this technology. As scheduled, the BD satellite navigation system will have a worldwide coverage by the end of 2020. Radio occultation studies in China have been highlighted in the recent decade. More and more feasibilities reports have been published in either domestic or international journals. Herein, some scenarios are proposed to assess the coverage of radio occultation based on two different phases of BD satellite navigation system. Phase one for BD is composed of GEO,IGSO and several MEO satellites. Phase two for BD consists mostly of 24 MEO satellites, some GEO and IGSO satellites. The characteristics of radio occultation based on these two phases are presented respectively.

Conference 9224: Laser Communication and Propagation through the Atmosphere and Oceans III

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9224-1, Session 1

Propagation of a Gaussian-beam wave in general anisotropic turbulence *(Invited Paper)*

Larry Andrews, Univ. of Central Florida (United States) and Townes Laser Institute (United States); Ronald L. Phillips, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and Townes Laser Institute (United States); Robert Crabbs, Townes Laser Institute, CREOL, Univ of Central Florida, Orlando (United States)

Mathematical models for a Gaussian-beam wave propagating through anisotropic non-Kolmogorov turbulence have been developed in the past by several researchers. In previous publications, the anisotropic spatial power spectrum model was based on the assumption that propagation was in the z direction but that circular symmetry was maintained in the orthogonal xy-plane throughout the path. In the present analysis, however, the anisotropic spectrum model is no longer based on a single anisotropy parameter—instead, two such parameters are introduced in the orthogonal xy-plane so that circular symmetry in this plane is no longer required. In addition, deviations from the 11/3 power-law behavior in the spectrum model are allowed by assuming power-law index variations . In the current study we develop theoretical models for beam spot size, spatial coherence, and scintillation index that are valid in weak irradiance fluctuation regimes as well as in deep turbulence, or strong irradiance fluctuation regimes. These new results are compared with those derived from the more specialized anisotropic spectrum used in previous analyses.

9224-2, Session 1

Comparison of the split-step method for various power spectral models

Heba Yuksel, Bogaziçi Üniv. (Turkey)

Turbulence remains an important unsolved problem of classical physics. When the collimated beams traverse the striated region, the beam first suffers random phase perturbations due to variations in the phase velocity within the medium. These phase variations in the propagating wavefront introduce small random changes in the direction of propagation of the beam. Thus portions of the once plane wavefront now propagate in different directions relative to other portions. As the beam propagates further, diffraction or angular scattering causes constructive and destructive interference which introduces fluctuations in amplitude as well as phase. These time-varying amplitude and phase fluctuations represent an undesired complex modulation of the carrier. We propose a phase-screen method based on a split-step approach to numerically solve the parabolic wave equation. The accuracy of the split-step solution for wave propagation in random media is proven by variety of studies but it will be the first in its field that the aperture averaging factor will be explored using the split-step method. In our previous work, the Modified Kolmogorov spectrum has been used in the modeling. In this work, different spectral models will be used and the effect of the model on the results will be investigated. All of our simulation results will be compared with other simulation models as well as empirical results. Our simulation will be unique and useful in developing a better turbulence model within all of the turbulence regimes.

9224-3, Session 1

Modeling of power spectral density of modified von Karman atmospheric phase turbulence and acousto-Optic chaos using scattered intensity profiles over discrete time intervals

Monish R. Chatterjee, Fathi H. A. Mohamed, Univ. of Dayton (United States)

In recent research, propagation of plane electromagnetic (EM) waves through a turbulent medium with modified von Karman phase characteristics was modeled and numerically simulated using transverse planar apertures representing narrow phase turbulence along the propagation path. The case for extended turbulence was studied by repeating the planar phase screens multiple times over the propagation path and incorporating diffractive effects via a split-step algorithm. Specific cases involving variable apertures and beam profiles were also examined in some detail. Owing to the random nature of the phase screen, repeated simulations over different times yield altogether different results and statistics. Accordingly, temporal statistics of the output field amplitude and phase may be computed. In this paper, a spatio-temporal statistical model is developed for atmospheric turbulence wherein slow and fast time turbulence scales are incorporated. Thereafter, the derived model is used to investigate the propagation of chaotic EM waves through such turbulence in order to assess if a chaotic wave suffers the same degree of signal degradation due to the turbulence as seen for non-chaotic waves. The chaos wave is generated via an acousto-optic Bragg cell under first-order feedback, known from recent work to be purely time-dependent. The expectation is that both unmodulated and modulated chaos waves (the latter occurring in the context of chaotic encryption of signals) will exhibit relative immunity to the effects of turbulence. Preliminary simulation results based on the above modeling are presented and some of the findings such as the amplitude and phase characteristics of the recovered EM wave profiles and the demodulated message are discussed.

9224-4, Session 1

Statistics of the turbulent phase in strong scintillation conditions

Mikhail I. Charnotskii, National Oceanic and Atmospheric Administration (United States)

Under strong scintillation condition the phase of the optical field propagating through turbulence contains phase singularities also called phase dislocations or optical vortices. Inevitably phase function is not continuous, and has branch cuts connecting singularities. Commonly used statistical description of phase in terms of phase structure function is based on the perturbation or smooth perturbation (Rytov) theory, and inherently is not capable of representing these singularities. Markov approximation for the optical waves propagation in turbulence does not use any perturbation assumptions, and predicts asymptotically normal probability distribution with zero mean for the optical fields of plane and spherical waves propagating through turbulence under strong scintillation conditions. Markov approximation also provides a relatively simple equation for the coherence of the optical field in the form of an exponent of so-called wave structure function D(r). For a normally distributed, zero-average, complex random field coherence function is sufficient to calculate all statistics of the field including the amplitude and phase. We derived equations for the single and two-point joint and marginal probabilities distributions of the amplitude and phase, and equation for the phase structure function that are valid for the strong scintillation condition when phase singularities are present. We found that probability distribution the phase of the phase difference at certain separation is

not Gaussian, and tend to a triangular shape at the large separations, as expected. Unsurprisingly, the two-point probability distribution of phase is a universal function of D(r) with the spatial dependence fully described by the wave structure function.

9224-5, Session 1

Modeling of the turbulent phase in strong scintillation conditions

Mikhail I. Charnotskii, National Oceanic and Atmospheric Administration (United States)

Monte-Carlo models of the turbulent phase are widely used in the studies of the optical propagation through turbulence atmosphere. However all algorithms, that are currently in use, generate continuous smooth phase samples. Meanwhile, it is well-known that under strong scintillation conditions turbulent phase has singularities, also called optical vortices, and phase is discontinuous across the branch cuts connecting the singularities. Markov approximation for wave propagation through random inhomogeneous media predicts that under the strong scintillation conditions optical field asymptotically has normal distribution with zero average. The sole sensible statistical moment of this complex random field is the two-point coherence function, which is readily available in the framework of the Markov approximation. We propose to generate the phase samples under strong scintillation conditions by first producing a complex normal random field with a given coherence function, and then determining the random phase as the argument of this complex random field. This approach allows generation of the two-dimensional discontinuous random phase samples that include phase singularities. Our Monte-Carlo algorithm is based on the Sparse Spectrum (SS) concept that was introduced in our earlier works, and can be modified to fit any desired shape of the turbulence spectrum. SS technique makes it possible to generate wide-band random fields and processes using a modest number of spectral components. We analyze the sensitivity of the phase samples statistics to the number of sparse spectral components, and check it against the theoretical results presented in the companion paper.

9224-6, Session 2

A flexible cross-talk simulator for multiple spatial-mode free-space optical communication *(Invited Paper)*

Jeffrey H. Shapiro, Massachusetts Institute of Technology (United States)

Achieving high photon information efficiency (many bits/detected-photon) and high spectral efficiency (many bits/sec-Hz) is impossible with a single spatial-mode free-space communication link [1]. This is so even though high photon information efficiency (PIE) can be obtained with pulse-position modulation (PPM) and direct detection [2], and high spectral efficiency (SE) can be achieved with quadrature amplitude modulation and coherent detection [3]. In particular, PPM's high PIE comes at the cost of low SE, and the PIE of coherent detection systems cannot exceed 3 bits/detected-photon. Achieving high PIE and high SE in the same vacuum-propagation system is possible, but it requires operation with 10's to 1000's of high-transmissivity spatial modes [1]. Consequently, such systems will likely be restricted to 1 to 10 km line-of-sight paths to avoid the need for inordinately large optics. Accordingly, terrestrial applications, with the concomitant atmospheric turbulence must be accounted for.

Recent theoretical work has established ultimate limits on the PIE/SE behavior of multiple spatial-mode free-space communications when the turbulence is uniformly distributed along the propagation path [4],[5]. These studies have considered operation both with and without adaptive optics, and explored three possible spatial-mode sets: focused-beam modes, Hermite-Gaussian modes, and Laguerre-Gaussian modes. Table-top experiments, using orbital angular momentum (OAM) modes — specifically the Laguerre-Gaussian modes with lowest-order radial dependence — have measured cross-talk and communication performance with and without adaptive optics for simulated thin phase-screen turbulence [6],[7].

In this paper we propose a simple and flexible cross-talk simulator for multiple spatial-mode free-space optical communication. Whereas the theory from [4],[5] would be exceedingly tedious to repeat for arbitrary distributions of turbulence along the propagation path, and the experiments from [6],[7] have been limited to one mode set and thin turbulence, our proposed simulator can realize arbitrary path-distributions and it can be used with arbitrary mode sets. Moreover, it can be readily implemented. All that is needed are two spatial light modulators: one for the transmitter's exit pupil and one for the receiver's entrance pupil. There are some limitations to this approach: it only simulates an approximation to Kolmogorov-spectrum turbulence, and it only provides information about the average modal cross-talk. Nevertheless, it could provide valuable information about the relevant merits of different mode sets when they are employed in conjunction with real modal multiplexers and demultiplexers.

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9224-7, Session 2

Performance analysis of MIMO FSO systems with radial array beams and finite sized detectors

Muhsin C. Gokce, Cankaya Univ. (Turkey); Canan Kamacıoglu, Çankaya Univ. (Turkey); Murat Uysal, Yahya K. Baykal, Ozyegin Univ. (Turkey)

Multiple-input multiple-output (MIMO) systems are employed in the free space optics (FSO) links to mitigate the degrading effects of atmospheric turbulence. In this paper, we consider a MIMO FSO system with practical transmitter and receiver configurations that consist of radial laser array beams and finite sized detectors. We formulate the average received intensity and the scintillation index as a function of receiver coordinates in the presence of weak atmospheric turbulence by using the extended Huygens-Fresnel principle. Then, integrations over the finite sized multiple detectors are performed and the effect of receiver aperture averaging is quantified. We further derive an outage

probability expression and determine the achievable diversity gain of this MIMO system in the presence of turbulence-induced fading channels. Using the derived expressions, we demonstrate the effect of several practical system parameters such as the radial displacement (ring radius) parameter, the number of array beamlets, the source size, the link length, structure constant and the receiver aperture radius on the outage performance.

9224-8, Session 2

Precoding design for multiple user massive MIMO indoor visible light communication system

Gang Chen, Tian Lang, Qian Gao, Univ. of California, Riverside (United States)

In this paper, we propose a precoding scheme by utilization convex optimization for multiple user massive multiple input multiple output (MU-MIMO) indoor visible light communication (VLC) where power for each LED is optimize by current channel condition to maximize channel reciprocity and reduction of latency. MU-MIMO increases data rate, enhances reliability, improves energy efficiency and reduced interference. Motivated by these merits, we first transformed a non-convex optimization VLC problem into a convex one by relaxing the non-convex constraint. With assumption with M- PAM signal constellation as input to the precoder, the converted problem is solved by MATLAB's convex optimization solver, CVX. The effectiveness of the scheme is illustrated by simulations using comparison with multiple user MIMO VLC.

9224-9, Session 2

Performance analysis of interference alignment with imperfect CSI in MIMO free space optical communications through turbulence

Yaqin Zhao, Guowei Li, Xin Zhong, Guanghui Ren, Harbin Institute of Technology (China)

To achieve a high speed transmission, an optical wireless multiple-input multiple-output (OMIMO) communication technique is proposed. Recent researches prove that interference alignment (IA) is a way to approach Shannon capacity. In order to improve OMIMO communication rate, IA is applied in OMIMO. However, an important concern about IA schemes lies on the requirement of the perfect channel state information (CSI). In this work, we study the performance of (IA) with perfect CSI in OMIMO through Kolmogorov turbulence. The decrease of total network capacity of several typical IA algorithms -- Min-WLI, Max-SINR and MMSE -- due to the estimation errors of CSI is analyzed. Based on the game theory, an improved interference alignment algorithm is presented to mitigate the influence of the imperfect CSI. Simulation shows that the improved IA algorithm has higher robustness than three IA algorithm mentioned. And the improved one can increase the multi-user networks capacity with imperfect CSI through turbulence.

9224-10, Session 3

Atmospheric effects and ultimate ranging accuracy for lunar laser ranging *(Invited Paper)*

Douglas G. Currie, Univ. of Maryland, College Park (United States); Ivan Prochazka, Czech Technical Univ. in Prague (Czech Republic)

In the near future, next generation lunar laser retroreflectors are planned for robotic deployment [1, 2]. With proper robotic deployment [3], these may support single photo-electron ranging accuracy at the 100 micron level or better. While there are available technologies for the support of ranging at this accuracy by advanced ground stations, the major question is the limit imposed on the ranging accuracy due to the atmosphere.
In particular, there are questions of the delay and broadening of a very narrow laser pulse. These effects may be roughly divided into three domains: High frequency effects due to atmospheric turbulence, low frequency effects due to atmospheric "slopes" and atmospheric waves and tides and spectral dispersion of the narrow pulse. Theoretical and experimental results will be discussed that address estimates of the magnitudes of these effects and the issue of precision vs. accuracy.

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9224-11, Session 3

World wide study of the performance of a sodium guidestar

Steven M. Zuraski, Univ. of Dayton (United States) and U.S. Air Force (United States); Steven T. Fiorino, Air Force Institute of Technology (United States)

This study quantifies the feasibility of a mobile sodium guidestar system. Simulations are run using the High Energy Laser End-to-End Operational Simulation (HELEEOS) software package with global sodium layer climatology data. Sodium layer data used were collected from the OSIRIS sensor package on board the ODIN satellite from 2005 through 2011 and provide a detailed global representation of the variable sodium layer occurring at an altitude of approximately 90 km in the atmosphere. This data is used in conjunction with the HELEEOS atmospheric propagation modeling to create realistic sodium guidestar models. The atmospheric effects for the laser propagation scattering model and creation of the sodium guidestar are defined in the worldwide probabilistic climatic database available in the HELEEOS software package. The simulations evaluate the performance of a guidestar as viewed from along the propagation path and from non-propagation path viewing angles for engagement scenarios in various locations on earth.

HELEEOS includes a fast-calculating, first principles, worldwide surface to 100 km, with extensions above 100 km to account for the sodium layer, atmospheric propagation and characterization package. HELEEOS is able to produce realistic evaluations of laser propagation, imaging, and adaptive optics systems by use of an end to end directed energy propagation model that incorporates probabilistic, climatological data from temporally and spatially variable meteorological, aerosol, and turbulence profiles at wavelengths from the ultraviolet to radio frequencies. Specifically, HELEEOS performs its propagation calculations utilizing the following algorithms, models and datasets: the cloud free line of sight (CFLOS) algorithm, Global Aerosol Dataset (GADS), Advanced Navy Aerosol Model (ANAM), the Adaptive Optical Compensation of Thermal Blooming (AOTB) model, and other physics based atmospheric propagation algorithms. HELEEOS was developed by the United States Air Force Institute of Technology (AFIT) under the sponsorship of the High Energy Laser Joint Technology Office (HEL-JTO).

9224-12, Session 3

Intelligent correction of laser propagation through turbulent media by using adaptive optics

Jonathan Ko, Chensheng Wu, Christopher C. Davis, Univ. of Maryland, College Park (United States)

Adaptive optics methods have long been used by researchers in the astronomy field to retrieve correct images of celestial bodies. A deformable mirror and a Shack-Hartmann sensor are used to correct the slightly distorted image after it has propagated through the earth's atmospheric boundary layer, which can be viewed as adding a relatively weak distortion in the last stage of propagation. However, the same strategy cannot be easily applied to correction in horizontal, deep turbulence situations. In fact, when the turbulence level becomes very strong (Cn2>10-13 m-2/3), limited improvements have been achieved in correcting the effects of turbulence. Thus, we propose a method that reconstructs the light field that reaches the camera, and provides instantaneous information for controlling a deformable mirror. An intelligent algorithm is applied that provides significant improvement in correcting images. In our work, the light field reconstruction has been achieved with a newly designed, modified plenoptic camera. As a result, by actively intervening with the coherent illumination beam, or alternatively giving it various specific pre-distortions, a better (less turbulence affected) image can be obtained. This strategy can also be extended to more general applications such as correcting laser propagation through random media and can help improve designs in free space optic communication systems.

9224-13, Session 3

Current status and challenges in optical turbulence simulations in various layers of the Earth's atmosphere

Ping He, Christopher G. Nunalee, Sukanta Basu, North Carolina State Univ. (United States); Mikhail A. Vorontsov, Univ. of Dayton (United States); Steven T. Fiorino, Air Force Institute of Technology (United States)

Random fluctuations of refractive indices, commonly known as optical turbulence, may have detrimental effects on optical wave propagation (i.e., beam wandering, degrading imagery, etc.) in various layers of the Earth's atmosphere. For upper troposphere and lower stratosphere, several empirical parameterizations (e.g., Hufnagel-Valley 5/7, Submarine Laser Communications, etc.) have been proposed to estimate the vertical profiles of refractive-index structure parameter (Cn2). These Cn2(z) profiles, however, are not site-specific and are time-invariant. In contrast, local parameterizations, such as those proposed by Dewan (1993) and Masciadri et al. (1999), can provide time- and height-dependent profiles of Cn2, and therefore are receiving growing interest in recent years. Utilizing the flow fields simulated by mesoscale weather models in conjunction with the local parameterizations can offer four-dimensional information for Cn2. It is needless to mention that all of the aforementioned parameterizations are empirical and most of them are not applicable in the atmospheric boundary layer (ABL). Fortunately, with the advances in computing power, large-eddy simulation (LES) is becoming a competitive approach to directly calculate Cn2 in the ABL, which is much more reliable and accurate than the aforementioned parameterizations. In this work, optical turbulence simulation results from several empirical and LES-based approaches are reported. We highlight the pros and cons of each of those approaches. Moreover, the simulated Cn2 fields are shown under different circumstances (e.g., flat terrain, coastal region, ocean islands, etc.), and the impacts of a few mesoscale atmospheric flow phenomena (e.g., low-level jets, von Karman vortex streets, etc.) on optical turbulence are discussed.

9224-14, Session 4

Phase and amplitude wave front sensing and reconstruction with a modified plenoptic camera

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A plenoptic camera can retrieve the direction and intensity distribution of collected light rays and allows for multiple reconstruction functions such as refocusing the light at a different depth and 3D microscopy. The principle is to add a micro-lens array to a traditional high-resolution camera to form a semi-camera array that preserves redundant intensity distributions of the light field and facilitates back-tracing of rays through geometric knowledge of the optical components. Though designed to process incoherent images, we found that the plenoptic camera shows high potential in solving coherent illumination cases such as sensing both the amplitude and phase information of a distorted laser beam. Based on our earlier introduction of a prototype modified plenoptic camera, we have developed the complete algorithm to reconstruct the wavefront of the incident light field. In this paper, the algorithm and experimental results will be demonstrated, and an improved version of this modified plenoptic camera will be discussed. As a result, our modified plenoptic camera can serve as an advanced wavefront sensor (compared to the traditional Shack-Hartmann sensors) when handling complicated cases such as coherent illumination in strong turbulence where interference and discontinuity of the wavefront is common. In wave propagation through atmospheric turbulence, this camera should provide a much more precise description of the light field, which would guide systems in adaptive optics to make intelligent analysis and corrections.

9224-15, Session 4

Advanced TIL regime for laser beam focusing in turbulent regime

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Atmospheric turbulence causes strong degradation in quality imaging of a remote image-resolved rough-surface object, laser beam focusing and long-range laser communication systems. Computational post-processing methods are applied to improve image quality. Alternatively, a target-in-the-loop (TIL) scheme, with its operation based on sequential round-trips of the laser field circulating between the emitting platform and an object, has been used to optimize beam focusing. However, existing practical realization of the Adaptive Optics-supported TIL systems didn't show convincing results when used to support a real-time laser beacon formation or signal dropout of laser-com systems. Various schemes of (TIL) have been suggested to address these issues, although lengthy iteration process, typically associated with this technique, makes its performance less effective, especially when dealing with laser beam propagation in deep turbulence, the scenario typical for maritime environment.

This presentation discusses an advanced configuration of TIL system (ATIL) that applies a nonlinear phase conjugation to perform a rapid adjustment of the wavefront of laser beam to mitigate atmospheric effects. The ATIL scheme allows to control the position on a remote imaged-resolved object of the laser beam and its spot size that is governed by the reciprocity of the counter-propagating beams and fidelity of the phase conjugation. In this presentation we will discuss present the results of the thorough analysis of ATIL operation, factors that affect its performance, its focusing efficiency and comparison of the experimental results with simulation.

9224-16, Session 4

Evolution of laser-induced plasma in solvent aerosols

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Characterization of the temporal and spatial evolution of laser-generated plasma in solvent aerosols is necessary for the development of potential applications which range from laser-induced ionized micro channels and filaments able to transfer high electric pulses over a few hundreds of meters, to the generation of plasma artifacts in air, far away from the laser source. This work is focused mainly on the visible and infrared spectrum. The influence of laser parameters (energy per pulse, pulse duration, repetition rate, wavelength, etc.) as well as the type of solvent and its composition on the plasma formation and evolution has been investigated. Laser-transmission losses through the aerosols and through the breakdown plasma as well as their effect on infrared plasma signature are to be presented.

9224-17, Session 4

Applications of laser induced filaments for optical communication links

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Laser beam propagation through optically transparent media is influenced by many parameters such as, energy, temporal and spatial beam profile, wavelength, repetition rate and etc.

Two competing physical processes are involved: self-focusing due to optical Kerr effect and optical diffraction. The index of refraction of an optically transparent media is affected by the presence of an intense electromagnetic field (which is associated with the laser beam). That can lead to a "lens like" effect and the laser beam will be focused due to the fact that the wave front is changing the index of refraction. The Laser Induced Plasma (LIP) generated will increase the dispersion of the beam due to its high density of electrons and ions, having a net result of focusing-defocusing cycles. The plasma channel created, actually a long filament which can extend few hundreds of meters, can be used as a low loss propagating media for a second laser beam. This paper explores the potential for propagating a second laser within the plasma channel for applications such as communications.

9224-18, Session 5

Visualizing the effects of distributed volume Non-Kolmogorov and anisotropic turbulence on incoherent imaging

Jeremy P. Bos, V.S. Rao Gudimetla, Air Force Research Lab. (United States)

While the effects of anisotropic turbulence on imaging are somewhat intuitive, the effects of changing power-law exponent, as well as the inner and outer scale of turbulence are less so. We have extended traditional methods of phase screen generation techniques to include an arbitrary direction in anisotropy and power law exponent. In addition, this phase screen model also allows variation of the inner and outer scale. The phase screen model itself is extended from the sub-harmonic enhanced spectral model described by Schmidt [1]. With anisotropic effects introduced via the scaling method described by Gudimetla, Holmes [2], et al. Simulation is accomplished using the horizontal-path imaging model described by Bos and Roggemann [3]. Image sequences previously described by Bos used the standard spectral model without sub-harmonic compensation and therefore underrepresented outer scale effects in anisoplanatic imaging.

Though phase screen generation and the simulation model will be discussed, the main point of this talk is to explore the effects of changing power-law specifically on the case of imaging through volume turbulence both objectively, through video sequences, and subjectively, using the MSE. We find that compensating for the outer scale using the sub-harmonic method significantly increases imaging distortion both subjectively and objectively as much as 50% or more. Values of power law exponent between 3 and 4 are also explored (Kolmogorov = 3.6). For values near 3 imaging distortions are negligible, while in contrast at exponent values near 4 images are severely blurred.

[1] Schmidt, Jason Daniel. "Numerical simulation of optical wave propagation with examples in MATLAB." Washington: SPIE, 2010.

[2] Gudimetla, V. S., et al. "Analytical expressions for the log-amplitude correlation function of a plane wave through anisotropic atmospheric refractive turbulence." JOSA A 29.5 (2012): 832-841.

[3] Bos, Jeremy P., and Michael C. Roggemann. "Technique for simulating anisoplanatic image formation over long horizontal paths." Optical Engineering 51.10 (2012): 101704-1.

9224-19, Session 5

Examining the validity of using a Gaussian Schell model for modeling an extended beacon on a rough perfectly reflecting surface

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In military applications that use adaptive optics, an extended beacon instead of a point source beacon is created at the target due to atmospheric turbulence and other factors. These beacons, which have a finite spatial extent and exhibit varying degrees of coherence, are typically modeled in existing literature as a Gaussian Schell Model (GSM) due to its analytical tractability. Earlier, a full wave computational technique was used to evaluate the scattered field from a rough impedance surface in vacuum. The results showed some deviations from GSM behavior. The present work uses a simulation approach based on Physical Optics (PO) approximation to study the scattering behavior in presence of atmospheric turbulence. A fully coherent Gaussian beam is propagated through atmospheric phase screens to the rough surface target plane. The PO current is computed on the rough surface and the scattered field right above the surface is determined. The scattered light is propagated through a second set of atmospheric phase screens and thus the double passage through the atmosphere is realized. The rough surface is simulated using statistical parameters derived from profilometer measurements of standard targets. Through multiple realizations of the atmosphere and the rough surface, the statistics of the scattered field is determined. The simulations are done with different strengths of turbulence and different roughness scales of the target. The results are compared with a GSM.

9224-20, Session 5

Scintillation reduction in multi-Gaussian Schell-model beams propagating in atmospheric turbulence

Svetlana Avramov-Zamurovic, Charles Nelson, Reza Malek-Madani, U.S. Naval Academy (United States); Yalong Gu, The

City College of New York (United States); Greg Gbur, The Univ. of North Carolina at Charlotte (United States); Olga Korotkova, Univ. of Miami (United States)

The recently introduced class of multi-Gaussian Schell-model beams is investigated via simulations and experimental data collection with regards to its intensity fluctuations. This class of random beams is constructed as a superposition of a finite number of classic Schell-model beams and is the two-parametric family characterized by the typical speckle size and the summation index. The higher values of the summation index are leading to the flatter intensity profiles with sharper drops at the edges. In order to generate the beam experimentally the phase-only Spatial Light Modulator was employed and the beam was sent through the horizontal atmospheric link of 375 meters on the ground of the US Naval Academy. The results of our simulations and data processing indicate that the scintillation index of the MGSM beam is substantially reduced for high values of summation index, on the order of forty. However, further increase in the index does not imply the significant improvement.

9224-21, Session 5

Laboratory implementation of partially coherent beams with super-Gaussian distribution

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A variety of partially coherent beams (PCBs) have been investigated due to their extraordinary propagation characteristics and potential for improving the performance of free space optical communications. Most of the pioneering work on PCBs has been theoretical without experimental verification. Recently some experimental approaches, such as computer-generated holograms, have been proposed and applied to generate PCBs including cosine-Gaussian-correlated Schell-model beams and ring-shaped beams. However, super-Gaussian beams, a class of beams which displays self-focusing at the lower order beam modes and “flat top” intensity distributions at higher beam modes, have not been demonstrated experimentally. In this work, we report the laboratory implementation of super-Gaussian PCBs with the help of a reflection-type spatial light modulator (SLM). The experimental results are consistent with theoretical predications. For example, the far-field intensity pattern for a beam with order less than 2 displays a narrow central spike. As the order increases, the intensity profiles become wider and flatter, i.e., more uniform in the center.

9224-22, Session 5

3D geometric modeling and simulation of laser propagation through turbulence with plenoptic functions

Chensheng Wu, William Nelson, Christopher C. Davis, Univ. of Maryland, College Park (United States)

Plenoptic functions preserve all the necessary light field information of optical events. Theoretical work has demonstrated that geometric based plenoptic functions can serve well in the traditional wave propagation equation known as the “scalar stochastic Helmholtz equation”. The phase screen model is the dominant method for 3D turbulence simulation, but this model has limitations in explaining the choice of parameters (on the transverse plane) in real-world measurements and finding proper correlations between neighboring phase screens (the Markov assumption breaks down). These limitations reveal some advantages of the equivalent geometric approach based on plenoptic functions. In the geometric approach, a continuous wave problem is reduced to a trajectory of discrete rays, which allows for convenience in parallel computing and conservation of energy is automatically guaranteed. Besides the pairwise independence of rays, the assigned refractive index grids can be directly tested by temperature measurements with tiny thermo-probes and combined with other parameters such as humidity level and wind speed. Furthermore, without loss of generality, one can break the causal chain in phase screen models by defining regional refractive centers which allow less affected rays to propagate through directly. Our work shows that the 3D geometric approach serves as an efficient and accurate method in assessing relevant turbulence problems with inputs of several environmental measurements and reasonable guesses (such as the value of Cn2). This approach will facilitate analysis and possible corrections in horizontal wave propagation problems, such as image de-blurring, prediction of laser propagation over long distances, and improvement to free space optic communication systems. In this paper, the plenoptic function model and relevant parallel algorithm will be presented, and the results and performance will be compared with those obtained using a phase screen model.

9224-23, Session 6

A hierarchy of atmospheric effects and laser beam detection *(Invited Paper)*

John S. deGrassie, Ike Bendall, Stephen M. Hammel, Space and Naval Warfare Systems Ctr. Pacific (United States)

The fundamental principles of laser beam detection from atmospheric scattering are well understood and have been used to make successful predictions of received laser power at off-axis detectors. Furthermore, models have been developed that can correlate atmospheric conditions to these predicted received powers. However, in addition to the first-order scattering effects, other “higher-order effects” (e.g., non-spherical aerosols, optical turbulence, and multiple scattering) will also play a role in determining the received power, affecting a laser beam’s detectability, either directly or indirectly. Using a validated model created by SPAWAR Systems Center, Pacific, we assess the relative impacts of these higher-order effects through model modifications and comparison with the fundamental prediction. We present a summary analysis of the higher-order effect in a hierarchy, quantifying their contributions to the laser beam detection problem and making recommendations on how best to modeling them and to what fidelity.

9224-24, Session 6

A reconsideration of the best wavelengths for free-space optics

Colin Reinhardt, John S. deGrassie, Stephen M. Hammel, Space and Naval Warfare Systems Ctr. Pacific (United States)

The selection of the “optimal” operating wavelength for Free Space Optical (FSO) communications systems has been a subject of some ongoing controversy over the past several decades. Practical FSO systems have been found to suffer severe performance degradation in adverse atmospheric visibility conditions (high extinction/low-transmission) such as fog, haze, and other atmospheric particulates (smoke, dust). Claims have been made that certain wavelengths offer superior performance and reduced attenuation for FSO systems.

We will revisit the problem of optical propagation through atmospheric particulates, and will show that the specific details of the selected particulate size distribution function (SDF), which specifies the particulates’ number density distribution by radius and the corresponding wavelength-dependent complex refractive indices, can significantly influence the total extinction/transmission behavior of various wavelengths and hence the choice of “optimal” wavelength. We will use a variety of realistic atmospheric SDFs to highlight the sensitivity of the “optimal” wavelength to the SDF composition details. A primary result will be a comparison matrix illustrating extinction performance at selected wavelengths across the spectrum of visible to LWIR for a variety of realistic and clearly-defined atmospheric SDF scenarios: fogs, hazes, smoke, and dust.

9224-25, Session 6

Simultaneous atmospheric extinction and scintillation estimation using a modulated beacon

Colin Reinhardt, David T. Wayne, Stephen M. Hammel, Kevin M. McBryde, Space and Naval Warfare Systems Ctr. Pacific (United States)

The ideal propagation of optical signals through the earth's atmosphere is degraded by two primary physical mechanisms: extinction due to suspended atmospheric molecules, aerosols, and particulates; and turbulence-induced spatio-temporal variations in both amplitude and phase, also referred to as scintillation. For many applications involving optical propagation, it is important to be able to accurately measure both these effects, to quantify their impact. Yet this challenge remains incompletely-solved.

We have recently developed the Dynamic Amplitude and Range Transmissometer (DART) which uses a modulated source to reduce background effects in order to measure atmospheric extinction and transmission with a high level of fidelity. We are now investigating using the same intensity-modulated source to simultaneously estimate the atmospheric optical turbulence and atmospheric transmission. Effects to be considered are:

• Correlated effects of extinction and scintillation along a common atmospheric channel

• The impact of using incoherent light (LED) versus coherent light (laser) as the source

• Aperture-averaging effects

• The influence of the system field-of-view

Theoretical formulation and solution of the optical propagation problem will be developed. Results from a recent field test campaign specially designed to provide a carefully controlled environment with well-characterized atmospheric conditions will be compared to the theoretical predictions and to computational Fourier wave-optics propagation simulations.

9224-26, Session 6

Investigation of scintillometer designs for dynamic path measurement

Stephen M. Hammel, David T. Wayne, Colin Reinhardt, Space and Naval Warfare Systems Ctr. Pacific (United States)

The characterization of atmospheric effects on a propagated laser beam is important to applications ranging from free-space optical communications to high-energy laser systems for ship defense. These applications are frequently developed for a dynamic propagation environment in which either one or both ends of the optical link are moving. The instruments are often constrained by size / weight / power limitations due to the platforms on which they will be installed.

The dynamic nature of the optical link induces several difficulties in link-path instrumentation: turbulence statistics on a continuously changing path are hard to interpret, and the optical instruments must be designed to maintain a high-quality link between beacon and receiver. We will review some of the scintillometer designs and we examine the associated data produced by these different instruments. Our primary emphasis is the characterization of marine atmospheres for laser propagation.

One particular focus of our investigation is the manipulation of the path-weighting function by varying combinations of receiver and transmitter aperture sizes. Careful selection of this aperture size combination enables a probe of the most relevant segment of the propagation path, or the exclusion of a problematic or distorting path end-point.

9224-27, Session 6

Propagation of light through ship exhaust plumes

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Looking through the atmosphere, it is sometimes difficult to see the details of an object. Effects like scintillation and blur are the cause of these difficulties. Exhaust plumes of e.g. a ship can cause extreme scintillation and blur, making it even harder to see the details of what lies behind the plume. It can sometimes be unavoidable to look through an exhaust plume, e.g. looking at the coast with the IR camera of a ship, it can happen that the exhaust plume is in between.

Exhaust plumes come in different shapes, sizes, and opaqueness and they depend on atmospheric parameters like wind speed and direction, as well as engine settings (power, gas or diesel, etc.). A CFD model is used to determine the flow field around the vessel including the plumes as a function of the aforementioned parameters. NIRATAM is used to perform the gas radiation calculations and to determine the amount of radiation the plume gives and the amount of radiation that propagates through the plume. An analysis was made of the amount of detail still visible through a plume under different conditions.

This plume module will be incorporated in the TNO EOSTAR-model, which provides estimates of detection range and image quality of EO-sensors under varying meteorological conditions.

9224-47, Session PMon

Double wedge scanning system with large range and high accuracy for satellite trajectory optical simulation

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For the inter-satellite laser communication, it is necessary to test and verify PAT performance of laser communication terminal on the ground before in flight test. Satellite trajectory optical simulator is one of the critical parts of the ground test and verification bed of laser communication terminal. It needs a large angular range and high accuracy to simulate communication of two satellites, i.e. from the field of view for the acquisition (an order of 10mrad) to the angular accuracy for the fine tracking (an order less than 1rad). We have developed a satellite trajectory optical simulator with two scanning system. One is coarse scanning system, which uses two wedges rotating around the same horizontal axis. The other is fine scanning system and has the submicroradian accuracy with two wedges rotating around the orthogonal axes, respectively. However, the whole simulator needs four large pieces of wedges and become complicated and costly. In this paper, we present new scanning system with only two wedges to realize the two combinations with coarse beam scanning and fine beam scanning to simulate the mutual angular movement between two satellites. Its optical principle is analyzed and it mechanical design is given.

9224-48, Session PMon

Effects of target reflective characteristics on laser ranging by comparing the BRDF model with the Lambertian model

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During the process of laser ranging, the interaction between the target and the laser beam has the close relationship with the light scattering characteristic of the target surface, which can be characterized by the bidirectional reflectivity distribution function (BRDF). This paper discusses the effects of target reflective characteristics by the BRDF model and the Lambertian model. The BRDF is definited by surface parameters, such as surface roughness, correlation lengths and refractive index, incident angle and wavelength, which the Lambertian model does not include the detailed properties of the target. The results shows BRDF is more precise than lambertian model in factual environment. The main work is the research on calculating and comparing the minimal detectable power of laser rangefinder obtained the two models under different incident angles and surface roughness. The angular dependence of the BRDF is related to the microscopic properties of the surface. It showed that when the surface roughness increases the detectable power decreases rapidly. Modeling and simulation of typical target shapes, plate and parabolic, are provided in this paper on the bases of the BRDF model, the echo signal is calculated to analysis the influence of different types of the target shapes. According the above study, it will provide some fruitful reference for further parameters choice of laser rangefinders and laser radar.

9224-49, Session PMon

Indoor demonstration of free-space picosecond two-way time transfer on single photon level

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The practical demonstration of an optical two-way time transfer based on single photon signal level has been completed. This approach enables to reach extreme timing stabilities and minimal systematic errors using existing electrooptic technologies. Attenuated picosecond lasers at 532 and 531 nm are used as a signal sources, the solid state photon counters based on silicon avalanche photodiodes are used as a signal detectors. Optical setup is based on passive elements only. Its scalability will be discussed. The crucial condition to almost eliminate systematic errors and to reach picosecond time transfer accuracy over free space communication channel is the maximum symmetry in experimental setup. In our indoor experiment we have achieved sub-picosecond precision and 3 ps accuracy. The entire system is compact and relatively simple. With two synchronized clocks the problem can be inverted and the same technique used for channel optical length online monitoring.

9224-50, Session PMon

Effects of de-blurring on background modeling used for surveillance in long-distance horizontal imaging

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Surveillance in horizontal long-distance imaging through the atmosphere commonly includes detection and tracking of targets such as people and vehicles. This operation is often very challenging, because of the image-distorting atmospheric effects that include mainly blur and spatio-temporal local movements of the scene as a result of the air turbulence at the imaging path. The scene is constructed from two elements: the background which is the scene without the moving targets, and the foreground, which includes only the moving targets of interest.

Automatic detection of moving objects is typically performed by subtracting a model of the background from the recorded video images in order to separate the moving targets. This background model is usually based on an anticipated temporal histogram of edge pixels in the recorded video.

The atmosphere-induced blur and the spatio-temporal movements have contradicting effects on the shape of a pixel's histogram mainly at edge locations in the image. The movements will influence towards a bimodal histogram, while the blur will increasing the likeliness of a single-lobe histogram.

In a recent study we analyzed theoretically and practically these contradicting effects and found that the model will likely have a single lobe (unimodal) at different imaging distances. However, if image de-blurring is performed, the histogram behavior may become bimodal. In this work we examine the effect of image de-blurring on the spatio-temporal image behavior. An automatic efficient image de-blurring is implemented and the image behavior is analyzed at edge locations for a large variety of imaging conditions.

9224-51, Session PMon

Adaptive optics for ocean surface wavefront sensing: polarized modulated directed beams

Katharine J. Jones, WBAO Consultant Group (United States)

A marine environment places challenges on laser-based naval optical systems: absorption, scattering, large scale reflective effects, and optical turbulence. It is a difficult environment for beam propagation on long horizontal paths near the ocean surface: water generally absorbs over all but short paths. Senors must achieve focusing and transmission of directed energy through atmosphere and above air-water interfaces. Laser guide stars are based on return of excited photons to measure and reverse distortion. For marine environments, the return signal has to be achieved by a strategically placed (i.e. buoy) reflecting surface above the air-water interface. Modulation must be calibrated for maximum return along with polarization for similarly maximized return. Sensor reflecting mirrors must be chosen to resist corrosion at the air-water level. There have been many well-thought out models to predict variable marine environments. We propose an adaptive optic polarized and modulated wavefront sensor to predict and mitigate distortion of imaging in a marine environment.

9224-52, Session PMon

Adaptive optical wavefront compensation system with space filter for satellite-to-ground laser communication link

Jianfeng Sun, Wei Lu, Yu Zhou, Ya'nan Zhi, Liren Liu, Shanghai Institute of Optics and Fine Mechanics (China)

Signal laser propagation will pass through the random atmosphere turbulence channel in satellite-to-ground laser communication application. The turbulence will cause the wavefront distortion in the receiver telescope front. For direct detection laser communication system, atmospheric turbulence can affect the coupling efficiency from space laser to the detector. For coherent detection laser communication system, Atmosphere turbulence not only affects the coupling efficiency, but also can seriously reduce the heterodyne detection efficiency. Coherent detection communication receiver must use small aperture telescopes or large aperture telescope with adaptive wavefront compensation system.

The compensation effect of the Traditional adaptive optics wavefront compensation system is related to the intensity of the actual atmospheric turbulence. In general, the stronger turbulence will cause the compensation effect decrease sharply. The residual wavefront error will affect the actual heterodyne detection efficiency. This paper proposes a new adaptive optics compensation system with spatial filtering function. The system can realize wavefront compensation effect is not influenced with the actual atmospheric turbulence intensity. But space filtering will cause energy loss. So, we should optimize the size of the pinhole according to the ability of adaptive optics compensation system itself. Through theoretical analysis and computer simulation, the compensation effects are obtained in different atmosphere turbulence in satellite-to-ground laser communication link.

9224-53, Session PMon

Indoor Visible Light Communication: Modeling and Analysis of Multi-state Modulation

Petr Koudelka, Jan Latal, Petr Siska, Jan Vitasek, Andrej Liner, Radek Martinek, Vladimir Vašinek, VŠB-Technical Univ. of Ostrava (Czech Republic)

The new dynamic direction of wireless networks development is based on the idea of networks utilizing the optical radiation in the visible spectrum VLC (Visible Light Communications). The impulse of this development direction was improvement in the semiconductor lighting technologies, namely the white power LEDs (Light Emitting Diode). These types of wireless networks are denoted as the optical wireless networks for indoor spaces utilizing optical radiation in the visible spectrum. The paper deals with the issue of deployment of multi-state modulations into the indoor visible light communications in LOS (Line of Sight) configuration. The first part of the paper focuses on design of modulation element (SMD LED matrix 3 x 3) and on the design of the entire light assembled from modulation elements with respect to the requirements for the optical power level, which must meet the requirement for the work surface illumination and transmission properties of the optical wireless communications (BER, SNR). The second part deals with the irradiation distribution in dark room in comparison with real room during used multi-state modulation scheme in both simulation and real measurement.

9224-28, Session 7

Atmospheric limitations on the performance of electro-optical systems *(Invited Paper)*

Karin U. Stein, Szymon Gladysz, Dirk P. Seiffer, Detlev Sprung, Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung (Germany)

Atmospheric effects limit the performance of any electro-optical system. Tasks such as long-range surveillance or laser beam propagation are especially affected by environmental effects. We will show the fundamental differences between imaging and propagation along a vertical vs. horizontal path.

9224-29, Session 7

Turbulence estimation and mitigation in horizontal path imaging

Kristofor Gibson, Space and Naval Warfare Systems Ctr. Pacific (United States)

Mitigating the effects of turbulence in imaging is an important capability for surveillance systems. For image capture applications, atmospheric turbulence causes global blur in isoplanatic conditions which prevents detection and identification of objects due to loss of important features. Free-space communication applications additionally suffer from these artifacts. The knowledge of the atmospheric characteristics can help improve the process of turbulence mitigation by applying enhancement filters designed according to optics parameters and turbulence characteristics. The additional problem is that estimating turbulence parameters require controlled equipment and known sources such that a transmitter and receiver pair are required.

In this paper we investigate a method that addresses both common problems where only a single imaging system (with known parameters) is used for observation in horizontal paths through the atmosphere. We first desire to investigate a method for automating the process of selecting the correct modulation transfer function such that the observed image can be deblurred; thus enhancing the received images. Secondly, we wish to investigate a method for estimating the refractive-index structure parameter.

We demonstrate the performance of this method with simulated data such that the camera and atmospheric conditions are known. Experiments were conducted and data collected in Point Loma, San Diego where atmospheric conditions were measured along with captured images of static scenes. We present the results of our approach with the simulated and real-world data. We discuss the issues with this type of approach and suggest plans for improving the method in the future.

9224-30, Session 7

Impact of large-scale atmospheric refractive structures on optical wave propagation

Christopher G. Nunalee, Ping He, Sukanta Basu, North Carolina State Univ. (United States); Mikhail A. Vorontsov, Univ. of Dayton (United States); Steven T. Fiorino, Air Force Institute of Technology (United States)

Conventional techniques used to model optical wave propagation through the Earth's atmosphere typically assume flow fields based on various empirical relationships. Unfortunately, these synthetic flow fields do not take into account the influence of transient macroscale and mesoscale (i.e. larger than turbulent microscale) atmospheric phenomena. Nevertheless, a number of structures that are characterized by various spatial and temporal scales exist which have the potential to significantly impact refractive index fields, thereby resulting dramatic impacts on optical wave propagation characteristics. In this presentation, we analyze a subset of spatio-temporal dynamics found to strongly affect optical waves propagating through these atmospheric structures. Analysis of wave propagation was performed in the geometrical optics approximation using a standard ray tracing technique. Using a numerical weather prediction (NWP) approach, we simulate multiple realistic atmospheric events (e.g. island wakes, low-level jets, etc.), and estimate the associated refractivity fields prior to performing ray tracing simulations. By coupling NWP model output with ray tracing simulations, we demonstrate the ability to quantitatively assess the potential impacts of self-organized atmospheric phenomena on optical ray propagation. Our results show a strong impact of spatio-temporal characteristics of the refractive index field on optical ray trajectories. In particular, in the numerical simulations we observed periodic deep optical energy density modulation inside optical receiver aperture. Such correlations validate the effectiveness of NWP models as they offer a more comprehensive representation of atmospheric refractivity fields compared to alternative methods based on the assumption of horizontal homogeneity. The primary results of this talk are: (1) quantification of the effects of accounting for atmospheric phenomena when considering optical ray propagation across long range trajectories and (2) demonstration of the capabilities of NWP as a tool for rectifying synthetic flow fields generally used for ray propagation modeling.

9224-31, Session 7

Estimation of optical turbulence in the atmospheric surface layer from routine meteorological observations:

an artificial neural network approach

Yao Wang, Sukanta Basu, North Carolina State Univ. (United States)

The estimation and prediction of optical turbulence (commonly characterized by Cn2) within the atmospheric surface layer (the layer adjacent to the land/water surface) are of great significance for both civil and military applications. Optical turbulence can be reliably measured by various types of research-grade instruments (e.g., small-aperture scintillometer); however, due to logistical and financial issues, these types of instruments and associated data are not widely available. In

contrast, standard meteorological variables (e.g., temperature, wind speed) are continuously measured by various organizations around the world with a very high spatio-temporal coverage. Over the years, several empirical relationships have been proposed to estimate Cn2 from these basic meteorological variables. The relationships range from polynomial regression model to similarity theories functions. In this presentation, we propose a new regression approach based on artificial neural network (ANN) and compare its performance against several existing formulations. To evaluate the accuracy of our proposed approach, we utilize observed Cn2 from several field experiments over the U.S. Great Plains.

For the prediction of basic meteorological variables over the next several hours to several days, traditionally, one employs complicated atmospheric models (commonly known as mesoscale models). In the second part of this presentation, we will demonstrate that our proposed ANN-based regression models can be used in conjunction with the mesoscale models for the prediction of Cn2. In addition to observational data, we will compare our regression approach against a state-of-the-art (yet, computationally expensive) coupled mesoscale-large-eddy simulation (LES) approach.

9224-32, Session 7

Reconstructing the prevailing meteorological and optical environment during the time of the Titanic disaster

Sukanta Basu, Chris G. Nunalee, Ping He, North Carolina State Univ. (United States); Steven T. Fiorino, Air Force Institute of Technology (United States); Mikhail A. Vorontsov, Univ. of Dayton (United States)

On April 15, 1912, more than fifteen hundreds innocent people lost their lives in one of the most tragic marine disasters in human history - the sinking of the Titanic vessel on her maiden journey. Over the years, various individuals and committees proposed diverse hypotheses (some are contentious) linking this disaster to nature's cruelty as well as to human follies. In a recent book titled "Titanic: A Very Deceiving Night", the author Tim Maltin has proposed a new theory which we believe sheds more light to the cause of this disaster. Most of his arguments are based on the detailed characterization of the meteorological and optical environment during the night of the disaster. For example, Maltin argues that due to anomalous refraction, the distress flares from Titanic appeared very low in altitude (in relation to Titanic's deck) to the nearby ship Californian. In other words, anomalous refraction might have wrongly influenced the decision of the captain of Californian to not come for rescue of Titanic's passengers.

Given the lack of observational data, some of Maltin's characterizations could be viewed as speculations with a high-degree of plausibility. In this presentation, we provide further evidence to Tim Maltin's theory by reconstructing the meteorological and optical environment utilizing a state-of-the-art meteorological model, a ray-tracing code, and a unique public-domain dataset called the Twentieth Century Global Reanalysis. We show that our simulation reliably captured the occurrence of an unusually high pressure system over the disaster site with calm wind and rapid temperature drop. In essence, the prevailing meteorological condition was representative of a strongly stratified boundary layer. The ray tracing simulations clearly show the signatures of anomalous refraction associated with this unusual meteorological condition. During this presentation, we also point out several limitations of our modeling study (e.g., crude parameterization of icebergs).

9224-33, Session 8

On the atmospheric propagation of Gaussian, Bessel, and airy beams

John P. Palastro, William Nelson, Chris C. Davis, Phil A. Sprangle, Univ. of Maryland, College Park (United States)

Bessel and Airy beams are often described as non-diffracting and self-healing—properties that appear to make them attractive alternatives to Gaussian beams for applications requiring propagation over long distances in atmosphere. To be truly non-diffracting and self-healing, however, their transverse field profiles would have to extend to infinity. In practice, the diffractive range of Bessel and Airy beams is determined by the finite size of the beam and its transverse features. As a result, realistic laser system constraints such as aperture size, intensity, and power diminish their apparent advantages. Furthermore, like any beam, Bessel and Airy beams acquire phase distortions from turbulence induced refractive index fluctuations, and undergo wander, spreading, and scintillation. To compare the performance of each beam, we simulate their propagation through atmospheric turbulence for both focused and collimated configurations, imposing realistic system constraints on the initial profiles. The simulation evolves each beam according to the paraxial wave equation with turbulence-induced refractive index fluctuations included through phase screens. For fixed power and aperture area, we find that the most effective beam for delivering power is a Gaussian beam, while the optimum beam for delivering on-axis intensity depends on the distance to the target.

9224-34, Session 8

Real-time hardware background subtraction

Galen Cauble, David T. Wayne, Space and Naval Warfare Systems Ctr. Pacific (United States)

When a coherent optical beam travels through the atmosphere the wave front is distorted by refractive index variations along the path. These turbulent effects can be characterized by calculating the scintillation index. We are concerned with detecting fluctuations of a laser signal in the presence of a background; but in order to calculate the scintillation index, the background signal must first be subtracted from the signal of interest. Traditionally, background is subtracted by first taking a data sample while the laser is off. The background sample is assumed to be a constant DC signal across the succeeding measurements and is simply subtracted in post-processing. This assumption may cause an inaccurate background measurement and thus a less accurate calculation of the scintillation index. In this paper we introduce a novel method of real-time background subtraction through hardware. This system has the benefit of reducing the error in traditional methods of background subtraction as well as increasing the dynamic range of the digitized signal. We built the hardware system and tested it over a maritime path near San Diego. The data from these tests ranked our method favorably alongside traditional methods of background subtraction.

9224-35, Session 8

Enhanced backscatter of optical beams reflected in atmospheric turbulence

William Nelson, John P. Palastro, Chensheng Wu, Christopher C. Davis, Univ. of Maryland, College Park (United States)

Enhanced backscatter (EBS), or the backward intensity amplification of light reflected in a turbulent medium, may be harnessed as an artificial guide star for free space optics applications. Using simulations, we investigate the EBS of optical beams reflected from mirrors, corner cubes, phase conjugate mirrors, and rough surfaces. The simulation evolves the beams according to the paraxial wave equation with turbulence-induced refractive index fluctuations included through phase screens. We consider both monostatic turbulence, where the index fluctuations remain constant for the outgoing and return paths, and bistatic turbulence, where the index fluctuations are uncorrelated for the outgoing and return paths. By examining the ratio of the reflected intensity in monostatic and bistatic turbulence as a function of Cn2, we identify the regime in which EBS is most distinctly observable. Standard EBS detection requires averaging the reflected intensity of many (~100) passes through uncorrelated turbulence. Here we present an algorithm called the "tilt-shift method." For each pass, a unique transverse phase

(tilt) is applied to the beam at the transmitter, and a coordinate translation (shift) is applied at the receiver. This results in the EBS from separate passes adding constructively at the center of the receiver, while the majority of each beam's intensity profile gets diverted to the receiver periphery. The "tilt-shift method" requires only a few (~10) passes and does not require the turbulence to be uncorrelated for each pass.

9224-36, Session 8

Experimental results on the enhanced backscatter phenomenon and its dynamics

Chensheng Wu, William Nelson, Jonathan Ko, Christopher C. Davis, Univ. of Maryland, College Park (United States)

Enhanced backscatter effects have long been predicted theoretically and have been experimentally demonstrated on a few occasions since the 1970s. In the field of atmospheric turbulence, the reciprocity of a turbulent channel generates a group of paired rays with identical trajectory and phase information that leads to a region in phase space with double the intensity and scintillation index. Though simulations based on phase screen models have demonstrated the existence of the phenomenon, few experimental results have been published describing its characteristics, and possible applications of the enhanced backscatter phenomenon are still unclear. With the development of commercially available high powered lasers and advanced cameras with high frame rates, we have successfully captured the enhanced backscatter effects from various reflective surfaces. In addition to static observations, we have also tilted and pre-distorted the transmitted beam at various rates to track the dynamic properties of the enhanced backscatter phenomenon to verify its possible application in guidance and beam and image correction through atmospheric turbulence. In this paper, experimental results will be described, and discussions on the principle and applications of the phenomenon will be included. Enhanced backscatter effects are best observed in certain levels of turbulence (Cn2≈10-13 m-2/3), and show significant potential for providing self-guidance in beam correction that doesn't introduce additional costs (unlike providing a beacon laser). Possible applications of this phenomenon include tracking fast moving object with lasers, long distance (>1km) alignment, and focusing of high-power corrected laser beams over long distances.

9224-37, Session 9

LED based underwater optical wireless communication

Shlomi Arnon, Etai Rosenkrantz, Ben-Gurion Univ. of the Negev (Israel)

Underwater optical wireless communication is an emerging technology, which can provide high data rate. High data rate communication is required for applications such as underwater imaging, networks of sensors and swarms of underwater vehicles. These applications pursue an affordable light source, which can be obtained by light emitting diodes (LED). LEDs offer solutions characterized by low cost, high efficiency, reliability and compactness based on off-the-shelf components such as blue and green light emitting diodes. In this paper we present our recent theoretical and experimental results in this field.

9224-38, Session 9

Modulated retro reflector for VLC applications

Etai Rosenkrantz, Shlomi Arnon, Ben-Gurion Univ. of the Negev (Israel)

Visible light communication (VLC) is a new emerging technology that uses standard visible light to transmit broadband data streams in addition to illumination. In our research we have theoretically studied an innovative device that can serve as a modulating retro-reflector (MRR) for VLC applications. The device comprises of a nanocoposite of ferroelectric thin-film embedded with noble metal nano-spheres. This MRR can be used in asymmetric communication links as an optical transceiver for mobile devices. The main conclusion from our study is that a nanocomposite based MRR can save power, complexity, dimensions and weight in comparison to standard communication links. This fact is very important for mobile platforms.

9224-39, Session 9

Statistical characterization of fluctuations of a laser beam transmitted through a random air-water interface: new results from a laboratory experiment

Arun K. Majumdar, Phillip Land, John Siegenthaler, Naval Air Warfare Ctr. Weapons Div. (United States)

New results for characterizing laser intensity fluctuation statistics of a laser beam transmitted through a random air-water interface relevant to underwater communications are presented. A laboratory water-tank experiment is described to investigate the beam wandering effects of the transmitted beam. Preliminary results from the experiment provide information about histograms of the probability density functions of intensity fluctuations for different wind speeds measured by a CMOS camera for the transmitted beam. Angular displacements of the centroids of the fluctuating laser beam generates the beam wander effects. This research develops a probabilistic model for optical propagation at the random air-water interface for a transmission case under different wind speed conditions. Preliminary results for bit-error-rate (BER) estimates as a function of fade margin for an on-off keying (OOK) optical communication through the air-water interface are presented for a communication system where a random air-water interface is a part of the communication channel.

9224-40, Session 9

Multiple phase-screen simulation of oceanic beam propagation

Nathan H. Farwell, Olga Korotkova, Univ. of Miami (United States)

Oceanic turbulence is simulated using a series of 2D phase-screens which is then used to investigate beam propagation in the ocean. Individual phase screens are created using a spatial power spectrum for oceanic turbulence that includes both temperature and salinity fluctuations. Numerical simulation is compared with experiment and with previous results in the literature. Intensity profiles as well as scintillation data is explored for several different turbulence parameters as well as several propagation distances examining a wide range of naturally occurring situations.

9224-41, Session 9

A novel method to optimize the wavelength for underwater free-space optical communications

Burton Neuner III, B. Melvin L. Pascoguin, Space and Naval Warfare Systems Ctr. Pacific (United States)

Wirelessly transmitting large volumes of information at high data rates underwater is becoming increasingly important for environmental monitoring and oil and gas exploration. Underwater free-space optical (FSO) communications addresses the aforementioned need by providing wireless high-data-rate links. Visible light transmission through seawater peaks in the blue-green spectrum (475 nm-575 nm), but local clarity

conditions, which are dynamic, strongly influence the actual maximum. We describe the development of a new laser-wavelength auto-selection algorithm and system for optimized underwater FSO communications. First, we present research on recreating various seawater types (from clear to turbid) in the laboratory using particle suspensions and dyes, which will enable wavelength-dependent transmission tests. Next, we show experimental results from optical water tube tests. We then compare simulation results to experimental data. Finally, we describe the development of the auto-selection algorithm. This system has the potential to improve underwater optical link reliability for high-data-rate communications.

9224-42, Session 10

Statistical characteristics of free space optical systems employing reception spatial diversity

Jose Paulo G. de Oliveira, Univ. de Pernambuco/FITec (Brazil)

Free space optical communication has become an attractive solution for data transmission due to its cost-effective, license-free, data integrity and high bandwidth characteristics. The performance of such systems, however, is highly affected by the effects of optical turbulence and beam misalignment. The modelling of such effects is still under investigation and concerns many scientists and engineers. Several mitigation methods have been proposed in order to diminish the optical turbulence effects on system performance. Once again, modelling these methods is often imprecise and mathematically challenging. Hence, it is important that, not only physical impairments, but also the benefits of the mitigation methods are well understood. For instance, multiple receiver apertures can be used to mitigate the turbulence fading by exploiting the advantages of spatial diversity. In this work the performance of a link employing spatial diversity at the receiver was investigated by analyzing two figures of merit: Bit Error Rate and Availability. Several geometrical arrangements of the receiver aperture were considered: one; two; three; and four apertures. The statistical properties of the photocurrent generated at the receiver – required for evaluating availability and bit error rate – were obtained by means of computer simulation using the Monte Carlo method. The presented results (BER and Availability) can be very helpful in designing a free space optical link with spatial diversity, since they are given in function of system configurations and impairment conditions, such as beam misalignment amplitude, turbulence strength and optical path distance.

9224-43, Session 10

Optical Ranging and Communication method based on All-phase FFT

Zening Li, Gang Chen, Univ. of California, Riverside (United States)

In this paper we propose a vehicular ranging and communication system. We use the LED array as the transmitter and the Photo Diode (PD) array as the receiver sensor. With this structure, we don't need a fine scanning mechanism to get better space resolution as usually used in Laser Detection and Ranging (LADAR) systems. In our proposed system, a vehicle fires a pulsed Spread Spectrum (SS) signature waveform as the ranging signal. Another vehicle which equips the same system receives this signature waveform then multiplies its bit information to this waveform and transmits it back to the first vehicle. Also, the SS waveform will be recorded by the second vehicle as the neighbor in its routing table to build the vehicular Networks. The first vehicle measures the time of flight to determine the distance. Even though other vehicles do not equip our proposed systems, we can still use the reflecting signal to acquire the distance information.

9224-44, Session 10

NLOS UV communication performance analysis for turbulence channel

Linchao Liao, Zening Li, Univ. of California, Riverside (United States); Tian lang, Univ of California Riverside (United States); Brian M. Sadler, Army Research Laboratory (United States); Gang Chen, Univ. of California, Riverside (United States)

With its solar blind and Non-Line-of-Sight characteristic, non-line-of-sight (NLOS) Ultraviolet (UV) communication received grant interest. However, as the communication range increases, the NLOS UV turbulence effect will deteriorate the communication performance, even with UV special turbulence mitigation effect which has not been comprehensively investigated. In this work, we propose a new Monte Carlo model to describe the entire process including scattering, turbulence and turbulence mitigation, which is the combination effect of coherent and non-coherent scattering new UV source. The simulation results are valuable for studying NLOS UV communication performance.

9224-45, Session 10

Inter-satellite coherent optical communication homodyne receiver locked frequency analysis and method

Guo Haichao, China Academy of Space Technology (China)

In free space optical homodyne receiver that analyze Residual carrier COSTAS loop, Inter-satellite LEO-GEO laser communication link frequency analysis, result from Doppler frequency shift 10GHz in the maximum range, LEO-GEO inter-satellite laser links between Doppler rate of change in the 20MHz/s. The optical homodyne COSTAS receiver is the application in inter-satellite optical link coherent communication system. The homodyne receiver is the three processes: Scanning frequency, Locked frequency and Locked phase, before the homodyne coherent communication. The processes are validated in lab., and the paper presents the locked frequency data and chart, LO laser frequency with triangle control scanning and receiving optical frequency is mixed less 100MHz intermediate frequency, locked frequency range between 100MHz and 1MHz basically, discriminator method determines mixing intermediate frequency less 1MHz between the signal laser and the LO laser with the low-pass filter due to frequency loop and phase loop noise. When two loops are running, the boundary frequency of laser tuning is fuzzy, so that we must be decoupling internal PID parameters. In the Locked frequency and phase COSTAS loop homodyne receiver gave the eye-diagram with Bit error rate 10E-7.

9225-24, Session PMon

Digital spiral-phase bi-photon imaging

Thandeka I. Mhlanga, Melanie McLaren, Alpha Ibrahim, Andrew Forbes, CSIR National Laser Ctr. (South Africa)

Quantum ghost imaging using entangled photon pairs has become an interesting field of investigation as it illustrates the quantum correlation between the photon pairs. In ghost imaging, an object is placed in the signal arm and a mobile (bucket) detector is placed in the idler arm, such that it scans through the transverse plane of the idler beam to give coincidence counting rate. The amplitude (shape) of the object is recovered from the measured coincidence count rate. We introduce a new technique using spatial light modulators encoded with appropriate digital holograms to recover not only the amplitude, but also the phase of the digital object. Down-converted photon pairs are entangled in the orbital angular momentum basis, which are typically measured using a spiral phase hologram. Thus encoding a spiral annular slit hologram into the idler arm, and varying it radially we can simultaneously recover the phase and amplitude of the object in question. We show that there is a good correlation between the encoded object and the reconstructed images, without the need of a 'bucket' detector as in the traditional ghost imaging which only recovers the amplitude.

9225-25, Session PMon

Review of representative free-space quantum communications experiments

Ronald E. Meyers, Keith Deacon, Arnold Tunick, U.S. Army Research Lab. (United States); Sanjit Karmakar, Univ. of Maryland, Baltimore County (United States)

No Abstract Available

9225-34, Session PMon

Thermal light imaging with non-classical resolution

Jane N. Sprigg, Tao Peng, Yanhua Shih, Univ. of Maryland, Baltimore County (United States)

No Abstract Available

9225-1, Session 1

Overcoming classical measurement limits through photon number correlations *(Invited Paper)*

Marco Genovese, Istituto Nazionale di Ricerca Metrologica (Italy)

In this talk we discuss as quantum correlation can enhance measurements capabilities, discussing three examples: target detection in a noisy environment, holometer and superresolution.

The first [2] is a quantum enhanced scheme preserving a strong advantage over classical counterparts even in presence of large amount of noise and losses. This work, inspired by [3], has been performed exploiting only photon number correlations in twin beams. Thus, for its simplicity it can find widespread use. Even more important by challenging the common believe that real application of quantum technologies is limited by fragility to noise and losses, it paves the way to their real application.

Then we describe as the same kind of correlations can find application in a completely different area of physics, i.e. in testing quantum gravity. Indeed, recently, effects in interferometers connected to non-commutativity of position variables in different directions were considered in two coupled interferometers [4], the ``holometer" [5]. We show that the use of quantum correlated light beams could lead to significant improvements.

Finally, we mention some recent development connected to super-resolution through high order correlation functions.

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9225-2, Session 1

Quantum ghost imaging research at ARL *(Invited Paper)*

Ronald E. Meyers, Keith Deacon, U.S. Army Research Lab. (United States)

No Abstract Available

9225-3, Session 1

Sub-Poissonian spatial correlations detected by novel photon number resolving camera *(Invited Paper)*

Radoslaw Chrapkiewicz, Michal Dabrowski, Michal Parniak, Wojciech Wasilewski, Univ. of Warsaw (Poland)

We present a novel experimental scheme of imaging spatially multi mode states of light with photon number resolution. The light is observed with the image intensifier coupled to the ultra low noise, fast CMOS camera. The camera is divided into subregions, for each we reconstructed its POVM in detector tomography process. We comprise high spatial resolution with photon number resolving ability. For instance we are able to effectively use several hundreds of regions at each counting up to 10 photons. We show the tomographic process of individual camera subregions of different sizes and thereafter the single mode and the two mode joint statistics reconstruction. Reconstructed POVMs differ significantly from those describing simple multiple on-off detectors therefore the tomographic process is essential.

Quantum correlations between different spatial modes of light can be revealed either by full photon statistics reconstruction or by calculating recently developed signatures of nonclassicality like Q-subbinomial parameter.

For high photon intensities fake sub-Poissonian features appears in both single and two mode moments, even with the use of classical states at the input. We show the proof of principle experiment where applying a statistics reconstruction we effectively remove this fake nonclassical features.

Finally we report observation of sub-Poissonian spatial correlations between time delayed modes of Raman scattering. The Raman scattering is generated in coherent atomic medium which stores phase and photon number information in atomic excitations. After an adjustable time delay we retrieve the excitation producing nonclassicaly correlated light.

9225-4, Session 1

Reduction effect of the accumulated number of ghost imaging by circulatory pattern

Kyuki Shibuya, Katsuhiro Nakae, Yasuhiro Mizutani, Tetsuo Iwata, Univ. of Tokushima (Japan)

Over the last decade, ghost imaging (GI) is a remarkable optical technique based on correlation measurements of light intensity between a reference and an object field. In this technique, an object information is obtained by using a point detector. It's striking that GI allow us to reconstruct the image of an object from an information of non-spatial resolution by using the intensity correlation. However, GI has the disadvantage that it needs a number of measurement to reconstruct a high visibility image. We propose, in this report, the reduction theory of accumulated number by applying an circulatory pattern based on the Hadamard matrix. The circulatory pattern consists of the two-dimensional binary pattern, which has characteristics of wave number without overlapping. Thus, an object information is obtained efficiently. In confirmation of this theory, we demonstrated the reduction effect of the accumulated number by numerical calculate and experiment for comparison of scanning imaging, traditional GI with circulatory pattern GI. As a result, the circulatory pattern GI shows a tendency to reduction effect of the accumulated number by the efficiency improvement of information acquisition. Additionally, in the result, the GI have potential of keeping visibility under low SNR condition by accumulation of an object information. In addition we will attempt to apply this method to monomolecular imaging.

9225-5, Session 1

Imaging single photons in non-separable polarization-spatial states

Enrique J. Galvez, Xinru Cheng, Colgate Univ. (United States)

Non-separable superpositions of polarization and spatial mode produce an unusual state of a single photon: a state of polarization that depends on the transverse position, and with the entire transverse mode containing all states of polarization. These are known as Poincare' modes of light. They contain single or multiple mappings of the points on the Poincare' sphere to points in the transverse mode of the light. We have done a measurement of the space-dependent state of polarization of single photons prepared in distinct 2x2 (qubit-qubit) and 2x3 (qubit-qutrit) non-separable superpositions of polarization and Laguerre-Gauss spatial states. We do this by encoding the state on heralded 702-nm photons and detect the state via projections of the state of polarization at discrete points on the transverse plane. The light was collected by scanning an iris over a wide-aperture fiber collimator connected to a single-photon detector. The polarization projections were used to calculate the Stokes parameters, and thus obtain the state of polarization of each point. The results are in excellent agreement with the expectations. The polarization patterns had a C-point polarization singularity in the center of the transverse wavefunction. We recreated all three types of singularities: lemon, star and monstar C-points.

9225-16, Session 2

Quantum repeater architecture and NV-based node technology *(Invited Paper)*

Kae Nemoto, National Institute of Informatics (Japan); Michael Trupke, Vienna Center for Quantum Science and Technology, Atominstitute (Austria); Simon J Devitt, Ashley M Stephens, Burkhard Scharfenberger, National Institute of Informatics (Japan); Kathrin Buczak, Tobias Nobauer, Jorg Schmiedmayer, Vienna Center for Quantum Science and Technology, Atominstitute (Austria); William J. Munro, NTT Basic Research Laboratories, NTT Corporation, (Japan)

We present a quantum repeater architecture build on a relatively simple device of module structure. It has a single NV center in an optical cavity, tuned to reflect light dependent on the stat of the electron of the NV center, |0> or |+1>. Two of these devices with photons can distribute entanglement between two electrons in the different cavities. For the long distance entanglement distribution, the nuclear spin of nitrogen 15 can be used to store the quantum state. The nuclear spin will be also used to build a cluster state to preform necessary gate operation at each node. We detail how such an entanglement distribution scheme works and can be applied to build quantum communication systems. We present a quantum repeater system as small as 10 modules to a fully scalable architecture, showing the performance and the requirements for modules.

9225-19, Session 2

Enhancement of quantum noise effect by classical error control codes in the intensity shift keying Y-00 quantum stream cipher *(Invited Paper)*

Kentaro Kato, Tamagawa Univ. (Japan)

The key concept of the quantum cryptographic Y-00 protocol is to degrade the signal detection capability of the adversary by enhancing the quantum noise effect at the adversary's receiver with the help of a secret key that is pre-shared between the legitimate users. In its implementation, not only the fundamental amount of the quantum noise effect to the adversary, but also the basic performance of it as a communication system depends on the choice of signal modulation format. Taking into account of this fact, several types of the Y-00 quantum stream cipher were proposed. In particular, recent progress of experimetal study on the intensity modulation based Y-00 quantum stream cipher, so-called ISK-Y00, shows that it is possible to provide high-speed, long-distant, and secure optical communications in practical situation. This motivates us to focus on ISK-Y00 rather than other types in this study.

For ISK-Y00, various randomization techniques for enhancing the quantum noise effect have been developed so far. In this study, we propose a new design method of the randomization technique called the deliberate error randomization (DER) in ISK-Y00. Since the adversary is allowed to use an optimal quantum receiver to reduce signal detection error, quantum signal detection theory plays an essential role in the evaluation of the quantum noise effect to the adversary caused by the installed randomization techniques. Based on this principle, we discuss how the quantum noise effect to the adversary is enhanced in ISK-Y00 with DER.

9225-9, Session 3

Quantum Statistical Testing of a Quantum Random Number Generator *(Invited Paper)*

Travis S. Humble, Oak Ridge National Lab. (United States)

Quantum technologies promise unique capabilities for applications in the computing, communication, and sensing domains. Designs of quantum devices most often apply idealized requirements to the quantum preparation and measurement subsystems. Inclusion of non-idealized subsystems often obscures the intended behavior at the cost of much greater model sophistication. Verifying that an actual device meets design requirements is therefore a challenging problem that is only further complicated by the observer effect, i.e., in which measurement of a (sub) system necessarily disturbs its quantum state.

We have developed techniques for verifying the behavior of quantum technology by using principles from model-based system engineering. Our MBSE approach is based on the homomorphism between the model representations of an abstract design and a derived physical implementation. By following the corresponding transformation on behavioral requirements, we are able to track expected physical behaviors and, more important, to formulate verification protocols that account for the observer effect. This requires both a well-defined abstract design of the device as well as well-defined rule sets for model transformation.

We demonstrate the approach using a prototypical quantum random number generator. With a photonic technology base, we demonstrate how a desired abstract behavior transforms into physical device requirements. We show how the designed behaviors can be verified with a unique form of quantum statistical testing that detects the presence of both randomness and bias in the physical device. We conclude by highlighting how model-based system design and its associated verification methods must influence future efforts to certify quantum technologies.

9225-10, Session 3

Conditionally random phase imprint of a beam profile: a spatial analogue to a non-Markovian process *(Invited Paper)*

Jandir M. Hickmann, Ana C. Ribeiro-Teixeira, Univ. Federal do Rio Grande do Sul (Brazil); Itamar V. S. de Lima, Univ. Federal da Paraíba (Brazil); Ricardo R. Bordalo Correia, Sandra D. Prado, Robert Fischer, Univ. Federal do Rio Grande do Sul (Brazil)

Designing the spatial coherence properties of light is fundamentally important to most applications in optics and photonics. Usually, efforts are made to increase the light's spatial coherence, through spatial filtering. Conversely, for the generation of random patterns, the spatial coherence length is small, such that signals measured by neighboring detection units are uncorrelated. This is the case of a random diffuser, which is the spatial analogue of a temporal Markovian process. Here we explore for the first time a spatial phase imprint analogue of a non-Markovian process inspired in the Sudoku puzzle.

Sudoku puzzles are a suitable basis for such conditional randomness in 2D and the topological entropy is an adequate measure for the randomness degree associated to the specific conditionally random phase profile, with respect to the completely random case.

In order to assess the prominent features of Sudoku light, mainly in how it differs from the limits of completely spatially coherent and incoherent lights, simulations were performed modelling propagation in different optical systems. In particular, for a double slit the diffraction pattern shows fringes in the outer lobes while having a minimum at the place of the zero's order.

Sudoku light can be experimentally generated using a spatial light modulator on e.g. a Gaussian light beam, for which the phases of different points in the beam profile are generated using a Sudoku solver for overlapping solutions.

These counter-intuitive properties of Sudoku light, while violating the spatial equivalent of the Markovian condition, may have some applications in the context of decay and initialization of quantum states.

9225-11, Session 3

Z_2 quantum memory implemented on circuit quantum electrodynamics *(Invited Paper)*

Thi Ha Kyaw, Ctr. for Quantum Technologies (Singapore); Simone Felicetti, Guillermo Romero, Enrique Solano, Univ. del País Vasco (Spain); Leong-Chuan Kwek, Ctr. for Quantum Technologies (Singapore)

We present a technique to store and retrieve single- and two-qubit states onto a parity protected quantum memory implemented on state-of-the-art superconducting circuit. Our proposal relies upon a specific superconducting circuit design that permits a tunable cavity-qubit coupling. The latter allows us to adiabatically change from null to ultrastrong coupling regime of light-matter interaction, where controllable and well-protected effective two-level systems are defined due to Z_2 parity symmetry. Storage and retrieval time of the qubit are in the order of a few nanoseconds, which is far below the effective qubit coherence time.

9225-12, Session 4

Complete temporal characterization of single photons *(Invited Paper)*

Adarsh S. Prasad, Univ. of Calgary (Canada); Zhongzhong Qin, Univ. of Calgary (Canada) and East China Normal Univ. (China); Travis Brannan, Univ. of Calgary (Canada); Alexander I. Lvovsky, Univ. of Calgary (Canada) and Russian Quantum Ctr. (Russian Federation); Andrew MacRae, Univ. of Calgary (Canada) and Univ. of California, Berkeley (United States); Arina Taschilina, Univ. of Calgary (Canada)

Photons are ubiquitous in quantum communication protocols. Temporal profiling of single photons is of major significance when it comes to designing devices interacting with them such as quantum memories. Here we demonstrate an experimental technique which allows us to fully characterize the photon in the time domain by determining its temporal density matrix. The characterized photon is heralded from four-wave mixing in an ensemble of three-level ? type atoms. The elements of the time domain density matrix are estimated from the autocorrelation data of the homodyne current corresponding to the signal photon. We record data at different local oscillator detunings which leads to phase evolution in the off diagonal terms of the autocorrelation matrix, thereby allowing us to calculate both real and imaginary components of the temporal density matrix. The temporal wave function corresponding to the dominant eigenvector of the temporal density matrix matches well with the prediction from theoretical calculations. Our technique will have applications in the development of quantum technologies focussed on efficient light matter interaction at single photon level.

9225-13, Session 4

Azimuthal spectrum after parametric down-convertion with radial degrees of freedom

Yingwen Zhang, Filippus S. Roux, Melanie McLaren, Andrew Forbes, CSIR National Laser Ctr. (South Africa)

Much experimental and theoretical work has been done to investigate the entanglement of photonic states in the Laguerre Gaussian (LG) basis generated through spontaneous parametric down-conversion (SPDC). The LG mode has both azimuthal and radial degrees of freedom yet most of the published works have focused on only the azimuthal degrees of freedom. Here we investigate the bi-photon state produced in SPDC in the LG basis with radial degrees of freedom both theoretically and experimentally. We derived theoretically an expression for the probability amplitude to detect LG modes with any combination of azimuthal and radial indices. Using this we determined the azimuthal Schmidt number $kappa$ for a range of radial indices and compared it with the $kappa$ we measured experimentally. There is good agreement between the theoretical and experimental results. We have found that a larger $kappa$ is obtained when increasing the radial indices of the signal and idler beams and also when the difference between the two radial indices increases. Experimentally we have demonstrated that it is possible to increase $kappa$ by at least 300% yet still maintaining decent coincidence count rate simply by using LG modes with slightly larger radial indices.

9225-14, Session 4

Quantum process tomography with unknown measurements *(Invited Paper)*

Michał Karpiński, Merlin Cooper, Brian J. Smith, Univ. of Oxford (United Kingdom)

Quantum process characterization is of crucial importance for implementation of realistic quantum communication and computation protocols. Full quantum process reconstruction is currently realized by means of quantum process tomography, which requires registering a detector response to a set of input states that have evolved under the unknown process. It relies upon both accurate preparation of the probe states and complete knowledge of the detector. Here we propose a novel protocol for the determination of a quantum process that alleviates the need for complete detector characterization.

The protocol is based on the recently introduced operational approach to quantum state estimation. [Rehacek et al. Phys. Rev. Lett. 105, 010402 (2010); Cooper et al. arXiv:1306.6431]. The detector is calibrated by constructing measurement outcome distributions for a set of known input states, the 'data patterns'. Subsequently the same input states are fed into the process under test, with resulting data patterns recorded as well. The process tensor is reconstructed by approximating the data patterns corresponding to the outputs of the unknown process as linear combinations of the calibration data patterns. This enables reconstruction of the process tensor in terms of tensor products of the input state density matrices. Our approach reduces the complexity of the numerical analysis and the experimental data required by limiting the reconstructed tensor to finite regions of input and output spaces. It offers a feasible route to propagate errors and examine quantum processes for large Hilbert spaces.

We demonstrate the feasibility of the approach for optical quantum processes by numerical simulations with experimentally realistic parameters. We successfully reconstruct process tensors of key processes such as multi-qubit logic gates, as well as continuous-variable operations.

9225-15, Session 4

Experimental test of error-disturbance uncertainty relations by weak measurement *(Invited Paper)*

Keiichi Edamatsu, Fumihiro Kaneda, So-Young Baek, Tohoku Univ. (Japan); Masanao Ozawa, Nagoya Univ. (Japan)

We experimentally test the error-disturbance uncertainty relation (EDR) exploiting a weak measurement for a single-photon polarization quit. The test is carried out by linear optical devices that realize variable measurement strength from weak measurement to projection measurement. The results show that Heisenberg EDR is violated throughout the range of our measurement strength and yet validates Ozawa and Branciard EDRs. A correct understanding and experimental confirmation of the error-disturbance uncertainty relation will not only foster an insight into fundamental limitations of measurements but also advance the precision measurement technology in quantum information processing.

9225-6, Session 5

High performance quantum communication without quantum memories *(Invited Paper)*

William J. Munro, NTT Basic Research Labs. (Japan); Kae Nemoto, National Institute of Informatics (Japan)

Quantum communication is necessary for any quantum internet, which at it's core generally requires quantum repeaters to form entangled links between remote locations. The performance of such links is limited by the classical signaling time between such locations, necessitating the need for long-lived quantum memories. In the talk we present the pipe-lined design of a communications network that neither requires the establishment of entanglement between remote locations nor the use of quantum memories. It can be shown that the rate at which quantum data can be transmitted through the network is only limited by the time required to perform efficient local gate operations. The scheme therefore has the potential to provide higher communications rates than previously thought possible.

9225-8, Session 5

Progress in Y-00 physical cipher for Giga bit /sec optical data communications *(Invited Paper)*

Osamu Hirota, Fumio Futami, Tamagawa Univ. (Japan)

Quantum Enigma Cipher is a new concept in the cryptography that may break the Shannon limit of cryptography.

Quantum Enigma Cipher powered by Yuen-2000 (Y-00) protocol is a novel quantum cryptography that relies on macroscopic quantum effects. So called Y-00 cipher at presnet is an encryption scheme where noise masking blocks reading the physical ciphertext consisting of the mathematical structure for realizing high security level. No such scheme is realized only by the mathematical encryption where ciphertext is correctly detected. Y-00 cipher provides high speed performance and a provable security. In the ideal setting, it may break the Shannon limit of the cryptography. In our Y-00 cipher, mathematical cipher and physical phenomena are combined. It features multi-level signaling by mathematical cipher and noise masking to hide the ciphertext in the quantum noise and other channel noises for disabling detecting correct ciphertext by an eavesdropper. In the report, experimental demonstrations for secure optical fiber communication using intensity modulated Y-00 cipher are summarized and detailed performance of noise masking effect is introduced.

9225-17, Session 5

143 km free-space quantum teleportation *(Invited Paper)*

Thomas Herbst, Univ. Wien (Austria); Xiao-Song Ma, Yale Univ. (United States); Thomas Scheidl, Institut für Quantenoptik und Quanteninformation (Austria); Bernhard Wittmann, Institut für Quantenoptik und Quanteninformation (Austria) and Univ. Wien (Austria); Rupert Ursin, Institut für Quantenoptik und Quanteninformation (Austria); Anton Zeilinger, Institut für Quantenoptik und Quanteninformation (Austria) and Univ. Wien (Austria)

Quantum teleportation is a fundamental resource of many quantum information-processing protocols. By using quantum teleportation, one can circumvent the no-cloning theorem and faithfully transfer unknown quantum states. It can also be used to create entanglement between formally completely independent particles via the process of entanglement swapping, which will be of utmost importance in a future quantum communication network, since it enables the global interconnection of quantum computers.

In order to prove the feasibility of quantum teleportation under optical link attenuations that will arise in a future space-application scenario, we extended the communication distance to 143 km, employing an optical free-space link between the two Canary Islands of La Palma and Tenerife.

This work proofs the feasibility of ground-based free-space quantum teleportation. With our setup we were able to achieve coincidence production rates and fidelities to cope with the optical link attenuation, resulting from various experimental and technical challenges, which will arise in a quantum transmission between a ground-based transmitter and a low-earth-orbiting satellite receiver. In particular the average state fidelity for the teleported quantum states was more than 6 standard deviations beyond the classical limit of 2/3 and the process fidelity was 0.710+/-0.042.

This experiment represents a crucial step towards future quantum networks in space, which require space-to-ground quantum communication. The technology implemented in our experiment reached the required maturity both for satellite and for long-distance ground-based quantum communication. We expect that many of the features implemented here will be key blocks for future experiments.

9225-18, Session 5

FEC coding for QKD at higher photon flux levels based on spatial entanglement of twin beams in PDC *(Invited Paper)*

Fred Daneshgaran, California State Univ., Los Angeles (United States); Marina Mondin, Inam Bari, Politecnico di Torino (Italy)

Twin beams generated by Parametric Down Conversion (PDC) exhibit quantum correlations that have been effectively used as a tool for many applications including calibration of single photon detectors. By now, detection of multimode spatial correlations is a mature field and in principle, only depends on the transmission and detection efficiency of the devices and the channel. In [1], the authors utilized their know-how on almost perfect selection of modes of pairwise correlated entangled beams and the optimization of the noise reduction to below the shot-noise level, for absolute calibration of Charge Coupled Device (CCD) cameras. In further discussion with the author and his research group, the possibility of using the same basic principles for Quantum Key Distribution (QKD) was suggested.

The main advantage in such an approach would be the ability to work with much higher photon fluxes than that of a single photon regime that is theoretically required for discrete variable QKD applications (in practice, very weak laser pulses with mean photon count below one are used). The natural setup of quantization of CCD detection area and subsequent measurement of the correlation statistic needed to detect the presence of the eavesdropper Eve, leads to a set of QKD parallel channel models that are Discrete Memoryless Channels (DMC) with a number of inputs and outputs that can be more than two (i.e., the channel is a Multilevel DMC). This work explores Forward Error Correction (FEC) coding for information reconciliation over the resulting parallel DMCs.

[1] I. P. Degiovanni M. Genovese M.Gramegna A. Avella, G. Brida and P. Traina. Phys. Rev. A, 82:062309, 2010.

9225-20, Session 5

Information teleportation networks *(Invited Paper)*

Ronald E. Meyers, Keith Deacon, Arnold Tunick, U.S. Army Research Lab. (United States)

No Abstract Available

9225-21, Session 6

Towards large scale quantum information processing with trapped ions *(Invited Paper)*

Winfried K. Hensinger, Univ. of Sussex (United Kingdom)

To this point, entanglement operations on ion qubits have predominantly been performed using lasers. When scaling to larger qubit numbers however this becomes problematic due to the challenging engineering that might be required. The use of microwaves combined with a static magnetic field gradient overcomes this problem. Microwave entanglement gates operate on magnetic-field sensitive states which leave them vulnerable to decoherence due to fluctuating magnetic fields.

We demonstrate the use of dressing microwave fields to decouple an ionic qubit from magnetic field noise, significantly increasing its coherence time, and perform single-qubit gates using radiofrequency fields. By integrating permanent magnets within our ion trap we generate a field gradient of 24 Tm-1 and use this gradient to entangle a single trapped ion's internal and motional states and generate Schrödinger cat states. We also report the first realisation of driving motional sideband transitions with microwave dressed states, and demonstrate near perfect individual addressing of ions.

We will also present our work creating microfabricated ion trap architectures for quantum simulation and quantum computation. At Sussex, we have developed a multitude of ion chips including superconducting ion chips with integrated microwave resonators (expected Q 106) featuring vertical interconnect (VIA) technology, multilayer ion chips with gold electrodes and VIA technology, Silicon-on-insulator ion chips and chips with embedded current carrying wires. These chip technology platforms are used to produce X and Y junctions, 2D arrays, ion storage rings, vertical shuttling traps, and linear segmented architectures.

9225-22, Session 6

A waveguide frequency converter connecting rubidium-based quantum memories to the telecom C-band *(Invited Paper)*

Boris Albrecht, Pau Farrera, ICFO - Institut de Ciències Fotòniques (Spain); Xavier Fernandez-Gonzalvo, ICFO - Institut de Ciències Fotòniques (Spain) and Univ. of Otago (New Zealand); Matteo Cristiani, Hugues de Riedmatten, ICFO - Institut de Ciències Fotòniques (Spain)

Quantum repeaters rely on heralded entanglement between remote quantum memories. To achieve efficient entanglement, it is necessary that photonic quantum memories are connected to the optical fiber networks. However, most quantum memories operate in a wavelength range where the loss in optical fibers is significant. Hence a quantum interface allowing us to connect these quantum memories to the optical fiber network by converting the emitted photons to telecom wavelengths is needed for almost all applications in the context of quantum communication. This frequency conversion must be efficient, noise free and must maintain the quantum properties of the converted photon. Frequency down conversion using difference frequency generation in non linear crystals (DFG) enables the conversion of visible or near infrared light to telecommunications wavelengths and is thus ideally suited for quantum repeater applications. In this work, we present a solid state photonic quantum interface capable of connecting DLCZ quantum memories based on cold Rb atomic ensembles to the telecommunication network. It is based on DFG in a non-linear PPLN optical waveguide, in order to convert Rb resonant photons from 780 nm to 1552 nm. As proof of principle, we have successfully converted a heralded single photon emitted by the quantum memory. We showed that a significant amount of non classical correlations between the heralding and converted heralded photons is preserved during the frequency conversion process. These results show that integrated optical devices can be used as a practical and flexible interface capable of connecting quantum memories to the optical fiber network.

9225-23, Session 6

Principle for possible memory structures with extra high density by using the electron sharing mechanisms of atoms in an inflective orbit

Taner Sengor, Yýldýz Teknik Üniv. (Turkey)

Both of the qualitative and quantitative knowledge of electromagnetic fields in the inter-atomic scale bring useful applications. From this point of view, bringing some possible new sights and solutions to atom-electron-photon-atom and/or molecule interactions is aimed in the near-field at inter atomic scale and their potential applications. The electron sharing processes between neighbour atoms are considered as inflective surface system and inflective guiding processes. The critical pass and transition structures are derived. The structures involving trigging that transition mechanisms may be suitable to design extra high density and fast data storage processes.

The electron sharing processes between two near atomic system are modelled with gate mechanisms involving two distinct passages: continuous pass and discontinuous pass. Even if the stochastic processes are applicable at these cases theoretical approach putting an influence like inner and external dipole mechanisms fits best to the situation and provides almost deterministic scheme, which has potential to estimate some processes being able to design new electronics structures and devices. We call orbitron all of such structures and/or devices.

The boundary value problem of atomic system sharing an electron in the way of electron passage model is formulated in spherically inflective coordinate system. The wave phenomenon is studied near spherically inflection points. The analytical essentials are derived for the solution of Helmholtz's equation when inflective boundaries are included. The evaluation is obtained by the extracted separation method. The results are given by spherically inflective wave series. The method is reshaped for the solution of Schrödinger equation.

9225-35, Session 7

Rydberg excitation assisted light shift blockade in Rb atoms for realizing a collective state quantum bit and quantum memory *(Invited Paper)*

Selim M. Shahriar, May Kim, Yanfei Tu, Northwestern Univ. (United States)

An ensemble of non-interacting alkali atoms has emerged as a highly efficient and viable quantum memory element for extending the range of quantum communication links. In this system, the quantum information is stored in the first order, symmetric collective excitation of the meta-stable hyperfine transition in the ground state, which is long-lived, especially when the ensemble is generated from a magneto-optic trap. However, the same transition cannot be used for quantum information processing among two ensembles, such as the realization of a CNOT gate. We show that this constraint can be eliminated by making use of Rydberg excitations, which produces a light-shift mediated blockade effect so that the ensemble behaves as a single particle with a two level transition between the hyperfine states. We describe the constraints, such as the maximum number of atoms in the ensemble and the spatial extent of the ensemble, that must be met in order to ensure this behavior. We also describe an explicit protocol for realizing a CNOT gate, which is a universal gate for quantum computation, between two such ensembles placed inside a cavity with only a modest finesse and a large mode volume. When compared to a Rydberg-blockade based quantum bit using single atoms, this approach may have several advantages. First, the ensemble is relatively insensitive to the exact number of atoms. Second, the ensemble can be used both as an efficient quantum memory and a quantum bit.

9225-36, Session 7

Statistics, quantum coherence of thermal and pseudo-thermal light

Yanhua Shih, Univ. of Maryland, Baltimore County (United States)

No Abstract Available

9225-37, Session 7

On the delayed-choice quantum eraser with thermal light

Tao Peng, Hui Chen, Yanhua Shih, Univ. of Maryland, Baltimore County (United States); Marlan O. Scully, Texas A&M Univ. (United States)

No Abstract Available

Monday - Tuesday 18–19 August 2014

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9226-1, Session 1

Optical modeling for a laser phased-array directed energy system *(Invited Paper)*

Gary B. Hughes, California Polytechnic State Univ., San Luis Obispo (United States); Philip Lubin, Univ. of California, Santa Barbara (United States); Hugh O'Neill, California Polytechnic State Univ., San Luis Obispo (United States); Peter Meinhold, Jon Suen, Johanna Bible, Jordan Riley, Isabella J. Hummelgård, Univ. of California, Santa Barbara (United States); Mark Pryor, Vorticity, Inc. (United States); Miikka Kangas, Univ. of California, Santa Barbara (United States)

We present results of optical simulations for a laser phased array directed energy system. The laser array consists of individual optical elements in a square or hexagonal array. In a multi-element array, the far-field beam pattern depends on both mechanical pointing stability and on phase relationships between individual elements. The simulation incorporates realistic pointing and phase errors. Pointing error components include systematic offsets to simulate manufacturing and assembly variations. Pointing also includes time-varying errors that simulate structural vibrations, informed from random vibration analysis of the mechanical design. Phase errors include systematic offsets, and time-varying errors due to both mechanical vibration and temperature variation in the fibers. The optical simulation is used to determine beam pattern and pointing jitter over a range of composite error inputs. Design requirements for a phase and beam steering controller are developed from pointing jitter results and from requirements for power delivery in a stand-off directed energy system. Several case studies are presented, including a large planetary defense system using km class arrays. Results are also presented for a 1m aperture array with 10kW total power, designed as a stand-off system on a dedicated asteroid diversion/capture mission that seeks to evaporate the surface of the target at a distance of beyond 10km.

9226-2, Session 1

Mechanical design for a laser phased-array directed energy system

Hugh O'Neill, California Polytechnic State Univ., San Luis Obispo (United States); Philip Lubin, Univ. of California, Santa Barbara (United States); Gary B. Hughes, California Polytechnic State Univ., San Luis Obispo (United States); Mark Pryor, Vorticity, Inc. (United States); Peter Meinhold, Jon Suen, Miikka Kangas, Johanna Bible, Caio Motta, Jordan Riley, Isabella J. Hummelgård, Univ. of California, Santa Barbara (United States)

We describe the design for a stand-off laser phased-array directed energy system, intended for deflection and compositional analysis of an asteroid. System power is provided from a photovoltaic panel. We discuss both a large system for full planetary defense and a small version for testing on a spacecraft with close approach to an asteroid. Rough pointing of the array to the target is determined by spacecraft attitude control. Laser tips behind each optical element are mounted on 2-axis micropositioner stages; lateral movement of the laser tips behind each lens provides intermediate pointing adjustment for individual array elements. Each fiber tip is supported on the 3-axis piezo stage. Precision beam steering is accomplished by coordinated phase modulation across the array by z-position control of the fiber tips and electronic phase shifting. Each fiber is fed with a laser amplifier. Phase feedback from in front of the lens array to each phase controller provides a signal for beam formation adjustment (spot focus). Phase alignment is maintained to within lambda/10 1-sigma RMS across the entire array. For the 1m system and a 10km stand-off, a spot size on the target asteroid of a few cm FWHM provides sufficient energy to heat the surface to the vaporization point of crustal rocks. Mass ejection creates considerable reactionary thrust to divert the asteroid. The heated spot also provides a blackbody source that can be viewed from a spectrometer on the spacecraft; absorption by material in the vapor plume allows molecular composition analysis.

9226-3, Session 1

Frequency stabilized lasers for space applications

Michael Lieber, Michael Adkins, Robert Pierce, Robert Warden, Cynthia Wallace, Carl Weimer, Ball Aerospace & Technologies Corp. (United States)

Frequency stabilized narrow line-width lasers have a broad range of applications including precision metrology, spectroscopy, atomic clocks and relativistic geodesy. This technology will be a key enabler to several proposed NASA science missions. Although lasers such as Q-switched Nd-YAG are now commonly used in space, other types of lasers - especially low power, narrow linewidth semiconductors - require further development to advance their technology readiness.

In this paper we discuss a reconfigurable laser frequency stabilization testbed based upon a 1550 nm semiconductor laser, and end-to-end modeling to support system development and provide a bridge to space. Two important features enabling testbed flexibility are that the controller, signal processing and interfaces are hosted on a field programmable array (FPGA) which has space-qualified equivalent parts, and secondly, fiber optic relay of the beam paths. Given the nonlinear behavior of lasers, FPGA implementation is a key system reliability aspect allowing on-orbit retuning of the control system and initial frequency acquisition. The testbed features a dual sensor system, one based upon a high finesse resonator cavity which provides relative stability through Pound-Drever-Hall (PDH) modulation and secondly an absolute frequency reference by dither locking to an acetylene gas cell. To provide for differences between ground and space implementation, we have developed an end-to-end Simulink/ Matlab-based control system model of the testbed components including the important noise sources. This model is in the process of being correlated to the testbed data which then can be used for trade studies, and estimation of space-based performance and sensitivities.

9226-4, Session 1

Directed energy active illumination for near-Earth object detection

Jordan Riley, Philip Lubin, Univ. of California, Santa Barbara (United States); Gary B. Hughes, Hugh O'Neill, California Polytechnic State Univ., San Luis Obispo (United States); Peter Meinhold, Jon Suen, Johanna Bible, Isabella J. Hummelgård, Janelle Griswold, Brianna Cook, Univ. of California, Santa Barbara (United States)

On 15 February 2013, a previously unknown ~20m asteroid struck Earth near Chelyabinsk, Russia, releasing kinetic energy equivalent to ~570kton TNT. Detecting objects like the Chelyabinsk impactor that are orbiting near Earth is a difficult task, in part because such objects spend much of their own orbits in the direction of the Sun when viewed from Earth. Efforts aimed at protecting Earth from future impacts will rely heavily on continued discovery. Ground-based optical observatory networks and Earth-orbiting spacecraft with infrared sensors have dramatically increased the pace of discovery. Still, less than 5% of near-Earth objects

(NEOs) ?100m/~85Mton TNT have been identified, and the proportion of known objects decreases rapidly for smaller sizes. Low emissivity of some objects also makes detection by passive sensors difficult. We propose that an orbiting laser phased array directed energy system could be used for active illumination of NEOs, enhancing discovery particularly for smaller and lower emissivity objects. Laser fiber amplifiers emit very narrow-band energy, simplifying detection. We present results of simulated illumination scenarios, based on an orbiting emitter array with specified characteristics. Simulations indicate that return signals from small and low emissivity objects is strong enough to detect. We will discuss the possibility for both directed and full sky blind surveys and the resulting diameter and mass limits for objects in different observational scenarios. We will also discuss the ability to determine both position and speed of detected objects.

9226-5, Session 1

Effects of asteroid rotation on directed energy deflection

Isabella J. Hummelgård, Philip Lubin, Univ. of California, Santa Barbara (United States); Gary B. Hughes, Hugh O'Neill, California Polytechnic State Univ., San Luis Obispo (United States); Peter Meinhold, Jon Suen, Johanna Bible, Jordan Riley, Jane Wu, Univ. of California, Santa Barbara (United States)

Asteroids that threaten Earth could be deflected from their orbits using laser directed energy or concentrated solar energy to vaporize the surface; the ejected plume would create a reaction thrust that pushes the object away from its collision course with Earth. One concern regarding directed energy deflection approaches is that asteroids rotate as they orbit the Sun. Asteroid rotation reduces the average thrust and changes the thrust vector imparting a time profile of thrust. A directed energy system must deliver sufficient flux to evaporate surface material even when the asteroid is rotating. Required flux levels depend on surface material composition and albedo, thermal and bulk mechanical properties of the asteroid, and asteroid rotation rate. A limiting rotation period for gravitationally bound aggregates greater than 150m is observed at 2-3 hours; faster spin rates cause such aggregates to break apart based on gravitational binding energy calculations. Some objects with diameters smaller than 150m have been observed rotating considerably faster, and are likely monolithic rocks with internal tensile strength rather than pure gravitational binding. We use the observed distribution of asteroid rotation rates, along with an estimated range of material and mechanical properties, as input to a thermal-physical model. The model calculates the expected thrust profile for rotating objects. Stand-off directed energy schemes that deliver 10MW/m2 generate significant thrust for all but the fastest conceivable rotation rates.

9226-6, Session 1

Recent advances in theoretical modeling of laser ablation for asteroid deflection *(Invited Paper)*

Nicolas Thiry, Massimiliano Vasile, Univ. of Strathclyde (United Kingdom)

Over the past few years, a series of studies have demonstrated the theoretical benefits of using lasers ablation in order to mitigate the threat of a potential earth-striking asteroid. Compared to other slow-push mitigation strategies, laser ablation allows for a significant reduction in fuel consumption since the ablated material is used as propellant. A precise modeling of the ablation process is however difficult due to the high variability in the physical parameters encountered among the different asteroids (material properties, rotation rate, geometrical shape to name a few) as well as the scarcity of experimental studies available in the literature. In a previous attempt to model such a phenomenon, the thermal conduction was assumed to be essentially unidirectional, with the asteroid acting as a sink of infinite length. Later experimental results however demonstrated discrepancies between the measured conduction flux and the theoretical flux. Seemingly, part of the conduction flux absorbed under the laser spot is actually radiated back outside in the region adjacent to the laser spot. A tool was developed in Matlab in order to assess the additional energy loss due to these parietal radiations in function of the ablation temperature and the size of the laser spot. A new model was also created using the Anisimov-Knight boundary conditions on the edge of the Knudsen layer to obtain a relation between the mass flow and the ablation temperature. Injecting the additional radiation loss in the energy conservation law, the results of this new model and the updated previous model are compared with experimental results obtained with a 90W continuous-wave laser operating under vacuum on an Olivine sample.

9226-7, Session 2

Post-flight test results of acousto-optic modulator and acousto-optic tunable filter devices subjected to space exposure *(Invited Paper)*

Narasimha S. Prasad, NASA Langley Research Ctr. (United States); Sudhir B. Trivedi, Jolanta I. Soos Rosemeier, Brimrose Corp. of America (United States)

The objective of the Materials International Space Station Experiment (MISSE) is to study the performance of novel materials when subjected to the synergistic effects of the harsh space environment for several months. MISSE missions have provided unique opportunities for developing space qualifiable materials. Several laser and lidar components from NASA Langley Research Center (LaRC) were a part of the MISSE 7 mission. The MISSE 7 module was transported to the international space station (ISS) via STS 129 mission that was launched on Nov 16, 2009. The MISSE 7 module was brought back to the earth via the STS 134 that landed on June 1, 2011. The MISSE 7 module, that was subjected to exposure in space environment for more than one and a half year included, TEO¬2 based acousto-optic modulator and an acousto-optic tunable filter. Performance testing of these two devices is now progressing. In this paper, the results obtained so far on the post-flight performance testing will be discussed along with their pre-flight performance characteristics.

9226-8, Session 2

System engineering of photonic systems for space application *(Invited Paper)*

Michael D. Watson, Jonathan E Pryor, NASA Marshall Space Flight Ctr. (United States)

The application of photonics in space systems requires tight integration with the spacecraft systems to ensure accurate operation. This requires some detailed and specific system engineering to properly incorporate the photonics into the spacecraft architecture and to guide the spacecraft architecture in supporting the photonics devices. Recent research in product focused, elegant system engineering has led to a system approach which provides a robust approach to this integration. Focusing on the mission application and the integration of the spacecraft system physics incorporation of the photonics can be efficiently and effectively accomplished. This requires a clear understanding of the driving physics properties of the photonics device to ensure proper integration with no unintended consequences. The driving physics considerations in terms of optical performance will be identified for their use in system integration.

9226-9, Session Key

Microfossils and biomolecules in carbonaceous meteorites: implications to the possibility of life in water-bearing asteroids and comets *(Keynote Presentation)*

Richard B. Hoover, Univ. of Buckingham (United Kingdom) and Athens State Univ. (United States)

It has been known for more than two centuries that carbonaceous meteorites contain carbon and water. Recent isotopic analyses have conclusively established that the carbon and water content of these stones is indigenous and extraterrestrial. Since 1961, investigations carried out in many countries has established that these meteorites also contain extraterrestrial organic chemicals and complex biomolecules. Independent studies conducted in the United States, France, Russia and the United Kingdom has also shown that many of these meteorites also contain the remains of large and clearly recognizable microbial extremophiles. These include the fossilized remains of algae, diatoms, filamentous cyanobacteria and extinct forms such as acritarchs and hystrichospheres. EDAX data reveal the absence of nitrogen in these fossils. These results combine with the absence of long-lived life-critical biomolecules (e.g., protein amino acids, nucleobases and pigments) clearly establish that these recognizable remains may not be dismissed as modern (i.e. post-arrival) microbial contaminants. This presentation will review these results and consider implications to the possibility of microbial life on comets and water-bearing asteroids.

9226-10, Session 3

Sensitivity of rarefied gas simulations of satellite ground tests to gas-surface interaction models *(Invited Paper)*

Jason Cline, Timothy Deschenes, Jason Quenneville, Ramona S. Taylor, Spectral Sciences, Inc. (United States)

The space environment produces a number of performance challenges to satellite and spacecraft manufacturers that require measurements, including effects from hyperthermal atomic oxygen, charged particles, magnetic fields, spacecraft charging, ultraviolet radiation, micrometeoroids, and cryogenic temperatures. Ground tests involving a simulated space environment help explore these challenges, but also benefit from simulations that predict the anticipated physical phenomna, or help reconcile the measured observations to physical parameters.

One aspect of ground-test simulation is the rarefied gas dynamics, where physics-based particle simulations describe the behavior of gas molecules as they collide with each other and with condensed-matter (i.e., usually solid) surfaces. Simulations of these systems depend on models that describe the results of molecular collisions. Gas-gas interactions, especially with small molecules, are often very well characterized, even when chemistry is involved. The gas-surface interactions, however, typically suffer from a lack of parameters, often leaving the modeler to make the canonical assumption of a diffuse reflection with full thermal accommodation. The potential for heterogeneous chemistry, possibly with vibrationally-excited or radiating products, further exacerbates this issue.

We present rarefied-gas dynamics simulations for gas propagation in notional chamber tests. The simulations are performed for a variety of gas-surface interaction boundary conditions and sources, so that we may analyze and report under what conditions the gas-surface interaction model matters, and to what phenomena it is relevant. We review the gas-surface models, data needs, and potential validation pathways.

9226-11, Session 3

Determining the molecular origin of radiation damage/enhancement in electro-optic polymeric materials through polarized light microscopy *(Invited Paper)*

Javier Perez-Moreno, Skidmore College (United States)

Previous studies on the radiation effects upon polymer and polymer-based photonic materials suggest that the radiation resistance of the material is heavily dependent on the choice of polymer-host and guest-chromophore. The best results to date have been achieved with electro optic polymeric materials based on CLD1 doped in APC, which has resulted in improved performance at the device level upon gamma-ray irradiation at moderate doses. Still, our understanding of the physical mechanisms behind the enhancement of the performance is unclear. In this paper, we discuss how polarized light microscopy could be used as a means to quantify the effect of the different physical parameters that influence the optical response of electro-optic polymeric thin film samples.

9226-12, Session 4

Internal strain monitoring in composite materials with embedded photonic crystal fiber Bragg gratings *(Invited Paper)*

Thomas Geernaert, Sanne Sulejmani, Camille Sonnenfeld, Vrije Univ. Brussel (Belgium); Karima Chah, Univ. de Mons (Belgium); Geert Luyckx, Nicolas Lammens, Eli J. Voet, Univ. Gent (Belgium); Martin Becker, Institut für Photonische Technologien e.V. (Germany); Francis Berghmans, Hugo Thienpont, Vrije Univ. Brussel (Belgium)

The possibility of embedding optical fiber sensors inside carbon fiber reinforced polymer (CFRP) for structural health monitoring purposes has already been demonstrated previously. So far however, these sensors only allowed axial strain measurements because of their low sensitivity for strain in the direction perpendicular to the optical fiber's axis. The design flexibility provided by novel photonic crystal fiber (PCF) technology now allows developing dedicated fibers with substantially enhanced sensitivity to such transverse loads. We exploited that flexibility and we developed a PCF that, when equipped with a fiber Bragg grating (FBG), leads to a sensor that allows measuring transverse strains in reinforced composite materials, with an order of magnitude increase of the sensitivity over the state-of-the-art. In addition it allows shear strain sensing in adhesive bonds, which are used in composite repair patches. This is confirmed both with experiments and finite element simulations on such fibers embedded in CFRP coupons and adhesive bonds. Our sensor brings the achievable transverse strain measurement resolution close to a target value of 1 µstrain and could therefore play an important role for multi-dimensional strain sensing, not only in the domain of structural health monitoring, but also in the field of composite material production monitoring. Our results thereby illustrate the added value that PCFs have to offer for internal strain measurements inside composite materials and structures.

9226-13, Session 4

Fiber optical sensors for aircraft applications *(Invited Paper)*

Ralf D. Pechstedt, Oxsensis Ltd. (United Kingdom)

In this paper selected fiber optical sensors that are of potential interest for deployment in aircraft are discussed. The operating principles together with recent measurement results are described. Examples

include a high-temperature dynamic pressure sensor that has originally been developed for land-based gas turbine environments up to 1000°C and 20kHz bandwidth. Adding simultaneous temperature measurement capability yields a more accurate dynamic calibration factor and enables a higher resolution of 1•10-5FS. The introduction of a spectral interrogation technique extends the high-temperature capability to accurate static pressure measurements showing a pressure linearity < ±0.1%FS over 700°C and a low temperature cross-sensitivity to pressure < ±0.03%FS. The spectral technique is also employed to demonstrate an ultra-high sensitive pressure sensor for potential fuel systems applications with a resolution of ±0.025mbar. In principle, the sensor also offers the ability to distinguish between different types of working fluids. Further, a combined acceleration and temperature sensor prototype that could be used for condition monitoring of rotating components is demonstrated.

9226-14, Session 4

Synopsis of fiber optics in harsh environments *(Invited Paper)*

Ronald G. Pirich, Long Island Forum for Technology (United States)

Fiber optic technology is making significant advances for use in a number of harsh environments, such as air and space platforms. Many of these applications involve integration into systems which make extensive use of optical fiber for high bandwidth signal transmission. There are many benefits of fiber optic systems for air and space harsh environment applications, including minimal electromagnetic interference and environmental effects, lightweight and smaller diameter cables, greater bandwidth, integrated prognostics and diagnostics and the ability to be easily upgraded. To qualify and use a fiber optic cable in space and air harsh environments requires treatment of the cable assembly as a system and understanding the design and behavior of its parts. Many parameters affect an optical fiber's ability to withstand a harsh temperature and radiation environment. The space radiation environment is dependent on orbital altitude, inclination and time, contains energetic magnetically-trapped electrons in the outer Van Allen radiation belt, trapped protons in the inner belt and solar event protons and ions. Both transient and permanent temperature and radiation have an attenuation effect on the performance of the cable. This paper presents an overview of defining fiber optic system and component performance in harsh environments by identifying operating and storage environmental requirements, using appropriate standards to be used in fiber optic cable assembly manufacturing and integration, developing inspection methods and fixtures compliant with the selected standards and developing a fiber optic product process that assures compliance with each design requirement.

9226-15, Session 5

On life assessment of high reliability high power optical switch

Yuanjian Xu, Peter Chu, Boeing Satellite Systems International, Inc. (United States)

High data rate and long range free space lasercom links require multi-watt optical transmitter power, which creates a need for high power redundancy switches to ensure high payload reliability. The current state-of-the-art efficiency of 1550 nm high power optical amplifier (HPOA) is about 12%. An optical switch after the HPOA is thus desired to have minimum loss. A high power optical switch (HPOS) capable of switching more than 40 watts of optical power in single mode fiber has been previously demonstrated in the Transformational Satellite Communication System program. This paper describes the life assessment of the HPOS.

Prototype switches, in either a 1x2 or 2x2 configuration, have been subjected to pyro-shock test, vibration test, and vacuum operation. These switches showed no performance degradation as a result of the tests. Three prototypes were put on life-test by connecting them in series with CW 35 watts optical power – one switch was in fixed "cross" state, one was in "bar" state, and the third one was toggled. The switches showed no change in insertion loss after 60,000 switching cycles. Low optical power life-test continued on these switches. More than 30 million switching cycles have been accumulated, and the switches showed no mechanical failure. Close checking with more sensitive parameters such as on/off extinction ratio (ER) shows that the HPOS performance deteriorated gradually after test location movement. If we define HPOS life as ER decreases 3 dB, the HPOS life is about 3.2 million switching action, which is well suitable for various space applications.

9226-16, Session 5

Compact VCSEL-based laser array communications systems for improved data performance in satellites *(Invited Paper)*

Richard F. Carson, Mial E. Warren, John R. Joseph, Thomas Wilcox, David J. Abell, Kirk J. Otis, TriLumina, Inc. (United States)

Recent advances have produced two-dimensional VCSEL arrays that can be modulated at high data rates (10Gbps), while producing power levels up to several watts. These power and speed capabilities provide a core technology that enables compact wireless (free-space) optical interconnects. Such links provide numerous solutions for operational data link challenges; especially those related to Size, Weight and Power (SWaP). The arrays can be scaled by adding VCSEL elements while manipulating their beams by a combination of integrated lenses and external optics to enable high speed optical wireless data communications from contact to hundreds of meters. For advanced space platform data capability, these data links can be used to connect high bandwidth payloads to computing cores in boom-to-bus arrangements or enable box-to-box communication within the satellite without cables or connectors to form an optical data bus. This minimizes launch weight, reduces EMI, and can enable a variety of configurations according to the needs of specific space platforms. These compact links could be especially advantageous in compact configurations such as nano-satellites. VCSELs are known to be temperature resistant, radiation hard, and in their free space arrangement, these links eliminate the need for optical fiber. The array configuration of the VCSEL emitters further enhances baseline VCSEL reliability through an inherent redundancy and a "graceful degradation" model where any random element failures that may occur in the operational environment only reduce link margin slightly. We will report on performance and reliability results related to these free-space optical communication links.

9226-17, Session 5

Germanium devices for integrated photonic circuits *(Invited Paper)*

F. Kenneth Hopkins, Air Force Research Lab. (United States); Alexander C. Benken, Kevin M. Walsh, Univ. of Louisville (United States); John G. Jones, Kent Averett, Darnell E. Diggs, Air Force Research Lab. (United States)

No abstract available

9226-18, Session 5

Shockwave consolidation of nanostructured thermoelectric materials *(Invited Paper)*

Narasimha S. Prasad, NASA Langley Research Ctr. (United States); Patrick J. Taylor, U.S. Army Research Lab. (United States); David C. Nemir, TXL Group, Inc. (United States)

Nanotechnology based thermoelectric materials are considered attractive for developing highly efficient thermoelectric devices. Nanostructured thermoelectric materials are predicted to offer higher ZT over bulk materials by reducing thermal conductivity and increasing electrical conductivity. Consolidation of nanostructured powders into dense materials without losing nanostructure is essential towards practical device development. We have been successful in generating consolidated nanostructured bismuth telluride alloy powders by using shockwave technique. Shockwave consolidation is accomplished by detonating the nanopowder-containing tube by surrounding it with explosives. Amorphous nanostructured powders were produced using gas atomization process. The resulting shock wave propagation causes rapid fusing of the powders without the melt and subsequent grain growth. Using these consolidated materials, several types of thermoelectric power generator devices have been developed. Shockwave consolidation is anticipated to generate large quantities of nanostructured materials expeditiously and cost effectively.

In this paper, the technique of shock-wave consolidation will be presented followed by room temperature measurements of thermal conductivity, electrical resistivity and Seebeck coefficients of several samples of doped and undoped n and p nanostructured materials. Data analysis of these room temperature measurements have shown significant deviations from anticipated results suitable for developing efficient devices. These nanostructured TE materials are being considered for space based power generation.

9226-19, Session 6

Next-generation space solar cells *(Invited Paper)*

Joseph C. Boisvert, Daniel C. Law, Richard R. King, Eric M. Rehder, Philip T. Chiu, Xing-Quan Liu, William D. Hong, Shoghig Mesropian, Kenneth M. Edmondson, Scott B. Singer, Nasser H. Karam, Spectrolab, Inc. (United States)

The vast majority of satellites today utilize III-V GaAs-based solar cells for primary power generation. This power is used primarily for the satellite payload and for bus housekeeping. The state-of-the-art in this technology is the triple junction (TJ) solar cell that employs three solar subcells in series to build up a voltage of about 2.3 V in operation. Individual TJ cells are then assembled into series-interconnected strings to eventually produce up to about 100 V at the satellite bus. The latest generation of TJ solar cells from Spectrolab - the neXt Triple Junction or XTJ solar cell – converts 29.5% of the incident solar power into electrical power.

Next generation solar arrays that will be used to provide primary power to satellite propulsion systems (Solar Electric Propulsion or SEP) will be required to provide bus voltages exceeding 300 V with solar cell power conversion efficiencies of >33%. Spectrolab is presently developing 4, 5, and 6 junction solar cell technologies that will lead to higher efficiency cells - 33%, 35% and 37% respectively - that develop 2.9 V, 3.5 V and 4.5 V respectively for SEP applications. These solar cells employ inverted metamorphic material structures and/or direct semiconductor bonding technology to produce high material quality subcells needed to minimize conversion efficiency losses to parasitic thermal mechanisms that degrade performance in all semiconductor solar cells.

This paper will review these next generation solar cell technology foundations, present status and future performance drivers.

9226-20, Session 6

AlGaAsSb as a top cell material for InP-based triple-junction solar cells *(Invited Paper)*

Yiqiao Chen, SVT Associates, Inc. (United States)

Current III-V multi-junction solar cells are either GaAs- or Ge-based cells, which have achieved over 40% energy conversion efficiency. Thus far no report on InP-based multi-junction cells can be found in the literature due to the lack of wide bandgap material for top junction although there are perfectly lattice-matched-to-InP materials such as InGaAsP with the desired band gap from 0.8 to 1.5 eV for middle and bottom cells in triple-junction cells. AlAsSb (EX=1.85 eV; E?=2.5 eV) was proposed as absorber for thin film cells, however no experimental result can be found for Al(Ga)AsSb solar cells partially due to the inferior material quality and indirect bandgap of AlAsSb. One of the reasons for the inferior material quality is Al(Ga)AsSb with lattice matched to InP falls in the miscibility gap. In this work, digital alloy technique, capable to grow high quality materials with composition falling in miscibility gap, was employed to grow high quality Al(Ga)AsSb to realize Al(Ga)AsSb solar cells. Here Al0.75Ga0.25As0.56Sb0.44, with a direct gap of 1.95 eV, is used as an absorber material for top junction. It should be pointed out that Al0.75Ga0.25As0.56Sb0.44 is still an indirect bandgap material since its EX=1.72 eV and hence there will be some energy loss since the photon-generated electrons in Γ-valley will relax to the X-valley. However, the energy or efficiency loss is limited due to the small difference between-Γ-point and X-point (~0.23 eV).

In order to demonstrate the feasibility of AlGaAsSb as the top cell material, a test Al0.95Ga0.05As0.56Sb0.44/Al0.75Ga0.25As0.56Sb0.44 cell grown by MBE (molecular beam epitaxy) was fabricated and characterized. The measured energy conversion efficiency is 8.9% under simulated AM0 radiation without AR coating on cell surface. Considering the design of the AlGaAsSb cell and MBE growth of AlGaAsSb on InP is far from optimization, the initial experimental result is very encouraging.

9226-21, Session 6

Engineering polymer frontier orbitals for efficient photon harvesting *(Invited Paper)*

Sam-Shajing Sun, Tanya S. David, Norfolk State Univ. (United States)

A series of new conjugated polymers with evolving frontier orbitals (HOMOs and LUMOs) have been designed, synthesized, and characterized for potential polymer based photon harvesting device applications. The relationships between monomer or repeat unit side groups, frontier orbitals (HOMOs and LUMOs) of the polymer, and changes in optoelectronic and physical properties of the polymer systems has been systematically investigated and correlated. For instance, when comparing the properties of the newly synthesized polymers in two groups: sulfone-based and phenyl-based, the difference in thermal stability and optical properties were consistent when changing from the carbazole monomer unit to the terephthaldicarboxaldehyde. The polymers containing the carbazole unit exhibited increased thermal stability, blue shift of optical absorption, higher LUMO orbitals, and larger band gaps than their terephthaldicarboxaldehyde containing counterparts. These could be attributed to the higher electron density of the carbazole than the terephthaldicarboxaldehyde, and the possible deviation from planarity in the polymer main chain due to possible steric hindrance of the branched substituents. Though the changes in the HOMO and LUMO orbitals did not affect the open circuit voltage of the fabricated polymer solar cell devices, as expected, the bulky substituents and changes in planarity as a result of the monomer unit change did affect the solid state packing (governed by π-π interaction). This in turn affected the short circuit current and overall efficiency of the solar cell device.

9226-22, Session 7

Heterostructure engineering of type II superlattice detectors *(Invited Paper)*

Sanjay Krishna, The Univ. of New Mexico (United States)

Unipolar barrier structures such as nBn, CBIRD, M-structure, N-structure, pBiBn and cascade structures have taken advantage of the unique bandstructure engineering properties of the 6.1A InAs/GaSb/AlSb family. In this talk, I will review some of the approaches that we have developed

in our group nBn, pBiBn and cascade detectors. The performance characteristics of these detectors will be discussed in detail in the presentation.

Acknowledgements: I wish to acknowledge my collaborators (Profs. Brueck/Hayat group at UNM, Dr. Cardimona's group at AFRL, Prof. Perera's group at Georgia State University, Prof. Painter's group at Caltech, Profs. Padilla at Boston College, Drs. Igal Brener, David Peters and Ganesh Subramaniam at Center for Integrated Nanotechnology (CINT) and Dr. S.K. Noh and Dr. S.J. Lee from Korean Research Institute of Standards and Science (KRISS). This work would not have been possible with out the hard working members of the research group (Dr. E. Plis, Dr. Zhaobing Tian, Dr. Tom Rotter, Dr. Jun Oh Kim, J. Montoya, B. Klein, T. Sandy-Schuler, S. Godoy, M. Zamiri, A. Kazemi, L. Acosta, E. Dughie, Z. Taghipour, T. Garwood, C.Kadlec and F. Santiago). Work supported by AFRL, AFOSR, MDA, KOSEF-GRL, DARPA, and NSF.

9226-23, Session 7

Long wavelength infrared HgCdTe photodetectors exposed to proton radiation *(Invited Paper)*

Jeremy D. Bergeson, Silviu Velicu, Ramana Bommena, Stephen Fahey, EPIR Technologies, Inc. (United States); Vincent M. Cowan, Christian P. Morath, Air Force Research Lab. (United States)

Exposure to proton radiation degrades the performance of long wavelength infrared (LWIR) HgCdTe photodetectors to varying degrees depending on the dose and energy of the incident particles. We report an experimental characterization of test devices of multiple sizes and configurations designed to investigate the effect ionizing and non-ionizing proton radiation has on detector performance. Photodetector test devices are processed into LWIR HgCdTe material grown by molecular beam epitaxy on CdZnTe substrates. The array of test diode structures is hybridized to a fanout array, mirroring the architecture of bump-bonded focal plane arrays. This setup also minimizes the influence from the characterization itself, as can happen with manual probe characterization. Isolated diode structures with various diameters are used for perimeter-to-area analyses. Several mini-arrays of test diodes, in both 18 and 30 µm pitch, mimic the performance of photodetectors in 2D staring arrays. Furthermore, mini-arrays surrounded by guard diodes permit the characterization of the mini-arrays with independent biasing of the guard diodes.

9226-24, Session 7

High operating temperature midwave infrared photodetectors based on InAs/GaSb type II strained layer superlattices

David A. Ramirez, SKINfrared LLC (United States); Elena Plis, SKINfrared LLC (United States) and The Univ. of New Mexico (United States); Stephen A. Myers, SKINfrared LLC (United States); Laura A Treider, Eli Garduno, Christian P Morath, Vincent M Cowan, Air Force Research Laboratory (United States); Sanjay Krishna, The Univ. of New Mexico (United States) and SKINfrared LLC (United States)

The realization of high operating temperature (HOT) midwave infrared (MWIR) photodetectors would significantly relax the requirements imposed on the cooling system, which would lead to a reduction in the size, weight, and cost of the detection system. One of the most attractive material systems to develop HOT photodetectors is InAs/GaSb Type II Superlattices (T2SLs). This is due the ability of T2SLs materials to engineer the band structure of the device, which can be exploited to make devices with unipolar barriers. It has been shown that the use of unipolar barriers can dramatically reduce the dark current levels of the device, which is essential to realize HOT photodetectors. In this work, we present results on MWIR HOT photodetectors based on InAs/GaSb T2SLs. We have designed, grown, and fabricated band-structure engineered MWIR photodetectors based on the pBiBn architecture. At 200 K, the dark current level of the tested devices was 4 milliamperes per centimeter squared, and the zero-bias detectivity, measured at 4.5 microns, was 44 giga Jones.

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9226-25, Session 8

Effect of defects on III-V MWIR nBn detector performance

Gregory R. Savich, Daniel E. Sidor, Univ. of Rochester (United States); Vincent M. Cowan, Christian P. Morath, Air Force Research Lab. (United States); Gary W. Wicks, Univ. of Rochester (United States)

Detectors for space applications must be tolerant of increases in defects caused by exposure to radiation. In MWIR detectors, increases in defects typically result in an increase in dark current which increases electrical noise thereby degrading system performance. Although increasing the number of defects always increases dark currents, defect tolerant detector design schemes can minimize degradation in performance. The nBn detector architecture has shown a reduced susceptibility to defects when compared to the more standard, non-barrier architecture, pn-junction based photodiode.

When the number of defects in the lattice is increased, conventional photodiodes exhibit an increase in dark current with an activation energy of one half of the bandgap, indicative of the well understood Shockley-Read-Hall (SRH) generation in the depletion region. nBn detectors exhibit a near full bandgap activation energy when an increase in defects has caused the dark current to increase. This behavior can be described by the SRH model for generation in the neutral, n-type absorber region of the device and diffusion of these generated carriers.

Whereas the SRH generation model predicts a direct proportionality between defect concentration and defect-related dark current in photodiodes, it predicts that dark current in nBn devices is proportional to the square root of the defect concentration. This is experimentally validated via study of both nBn and pn junction devices exhibiting elevated defect concentrations due to lattice mismatch conditions and proton irradiation of devices on matched substrates.

Results show that nBn device architectures are more tolerant to increases in defects than conventional photodiode architectures as predicted by SRH theory. Furthermore, since the activation energy of the dark current of nBn devices with an elevated defect concentration is twice that of a pn junction under the same conditions, the nBn detector shows a faster reduction in these defect related currents when cooled.

9226-26, Session 8

In-situ minority carrier lifetime measurements at radiation sources for rad-hard IR detector materials

Geoffrey D. Jenkins, Air Force Research Lab. (United States)

Minority carrier lifetime is the key material parameter for space-based infrared detector performance, affecting both dark current and responsivity. Displacement damage due to energetic protons in space environments, however, significantly degrades the lifetime and thereby the detector performance. Here, progress towards a portable minority carrier lifetime measurement system employing time resolved photoluminescence (TRPL) is reported on. This system allows for minority carrier lifetime measurements to be taken at remote radiation sites and permits measurement of step-wise changes in the lifetime with proton dose for determining the lifetime radiation damage factor constant.

The pulsed laser driven TRPL test bed is used to interrogate materials of interest mounted in an optical cryostat held indefinitely at a desired temperature. Results of such measurements are discussed for several IR detector materials.

9226-27, Session 8

Biopolymers suitable for space environments
(Invited Paper)

James G. Grote, Fahima Ouchen, Air Force Research Lab. (United States); Perry P. Yaney, Univ. of Dayton (United States)

No Abstract Available

9227-12, Session PMon

Phase detection experiment for the down-looking synthetic aperture imaging ladar with electro-optic modulation

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Down-looking synthetic aperture imaging ladar (SAIL) consists of a transmitter of two coaxial and deflected polarization-orthogonal beams; the two polarization-orthogonal beams have spatial parabolic phase difference at the focal plane of main lens. The beams are coaxially recombined before transmission. The receiver is designed for self-heterodyne detection of the two coaxial beams. The traditional measurement used mechanical scanning and optical wavefront transformation component to produce beams with spatial parabolic phase difference, the phase modulation was not enough high speed. Compared with traditional down-looking SAIL with mechanical scanning, the innovation in our experiments is that the phase modulation is the whole region covering the target and use electro-optic modulation with high modulation rate. Due to the high modulation rate without mechanical scanning, this technique has a great potential for applications in extensive synthetic aperture imaging ladar fields.

9227-14, Session PMon

Speckle effect in a down-looking synthetic aperture imaging ladar

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Down-looking synthetic aperture imaging ladar (SAIL) is based on the wavefront transformation and regulation by optical techniques. It has overcome many difficulties in side-looking SAIL. Instead of using the linear chirp signal, the down-looking SAIL transmits two coaxial counter-deflected polarization-orthogonal beams with spatial parabolic phase difference. After self-heterodyne detection and phase complex-valued processing, a linear phase modulation proportional to the lateral distance of target point in the orthogonal direction of travel and a quadratic phase history centered in the longitudinal position of target point in the travel direction are respectively obtained and collected. Given that the laser is employed as the transmitted optical source, speckle effect must exist and influence the down-looking SAIL inevitably. In the down-looking SAIL, temporally varying speckle effect are introduced by the angular deflecting other than the chirp laser signal. Furthermore, under the coaxial heterodyne, phase variations caused by speckle effect are compensated, leaving only the amplitude variations of speckle effect. Reconstructed by the Fourier transform algorithm in the orthogonal direction of travel and quadratic match filtering in the travel direction, the two-dimensional image with speckle effect shows the change of image contrast and resolution and the decline of the luminance.

9227-15, Session PMon

Phase error suppression by low-pass filtering for synthetic aperture imaging ladar

Zhiwei Sun, Peipei Hou, Ya'nan Zhi, Jianfeng Sun, Qian Xu, Zhiyong Lu, Liren Liu, Shanghai Institute of Optics and Fine Mechanics (China)

The fundamentals of synthetic-aperture imaging ladar (SAIL) originate in the synthetic-aperture radar (SAR) in radio domain. SAIL can provide centimeter-class resolution with an aperture no larger than a few meters on an observation distance of thousand kilometers or more. Compared to SAR, SAIL is more sensitive to the phase errors induced by atmospheric turbulence, undesirable line-of-sight translation-vibration and waveform phase error, because the light wavelength is about 3-6 orders of magnitude less than that of the radio frequency. This phase errors will deteriorate the imaging results. In this paper, an algorithm based on low-pass filtering to suppress the phase error is proposed. In this algorithm, the azimuth quadratic phase history with phase error is compensated, then the fast Fourier transform (FFT) is performed in azimuth direction, after the low-pass filtering, the inverse FFT is performed, then the image is reconstructed simultaneously in the range and azimuth direction by the two-dimensional (2D) FFT. The mathematical analysis by virtue of data-collection equation of side-looking SAIL is presented. The theoretical modeling results are also given. In addition, the verified experiment is performed employing the data obtained from a SAIL demonstrator. The high-frequency phase error can be effectively eliminated hence the imaging results can be optimized by this algorithm.

9227-1, Session 1

Hybrid curvature and modal wavefront sensor

Shihao Dong, Univ. Stuttgart (Germany); Tobias Haist, Tom Dietrich, Wolfgang Osten, Institut für Technische Optik (Germany)

The crosstalk effect considerably limits the capability of holography-based modal wavefront sensing (HMWS) when measuring wavefronts with large aberrations. In this contribution, we introduce a curvature-based measurement technique into HMWS to extend the dynamic range and the sensitivity of HMWS. Fourier holograms for the curvature sensing and HMWS are multiplexed and further binarized to obtain one compact design, which combines two sensor principles in one scheme. When the aberrated beam illuminates the hologram, the diffraction image in the Fourier plane of the convergent lens shows two characteristic patterns, the two signals for sensing the local curvatures of the wavefront and the diffraction pattern for the HMWS. The amplitude of Zernike terms can be reconstructed either using an optimized simulated annealing process by comparing the simulated and captured curvature data or using a direct reconstruction matrix method. If the input aberrations are large, the dominating Zernike terms are first detected via the curvature sensing and compensated using a wavefront correcting device, e.g. a membrane mirror. The system then switches to HMWS to obtain better sensor sensitivity and accuracy with reduced aberrations. Additionally, the curvature sensing can benefit the HMWS by providing supplemental information in sensing high spatial frequencies with higher sensitivity.

In this contribution we explain the theoretical model of the hybrid sensor. To test the performance of the sensor, extensive simulations have been carried out with random aberrations generated according to the atmospheric turbulence model. The simulation results validate the proposed method.

9227-3, Session 1

Nanosatellite wavefront sensing for in-space demonstration of deformable mirrors

Anne D. Marinan, Kerri L. Cahoy, Caitlin Kerr, Massachusetts Institute of Technology (United States); Matthew Webber, Harvard-Smithsonian Ctr. for Astrophysics (United States); Ruslan Belikov, Eduardo A. Bendek, NASA Ames Research Ctr. (United States)

High-actuator density deformable mirrors are key optical components in future space telescopes designed to obtain high-contrast images for astronomy. These mirrors correct image plane aberrations and speckles caused by imperfections, thermal distortions, and diffraction in the

telescope and optics that would otherwise corrupt the wavefront and ruin the desired contrast. While high-actuator count deformable mirrors have been developed for ground-based applications, space telescope platforms require low-power, small form-factor drive electronics and space-qualified devices. There have not yet been space-qualification and long-term on-orbit performance analyses of such systems.

We have designed a CubeSat (3U) mission to characterize and demonstrate the performance of high-actuator density deformable mirrors on orbit over an extended period of time (months). The mission makes use of a 3U CubeSat bus with a 10 x 10 x 15 cm volume reserved for the optical payload. The mirror intended for this mission is a 32-actuator Boston Micromachines Mini deformable mirror, though the design is flexible and can be applied to mirrors from other vendors. The on-orbit characterization procedure requires measurement of individual mirror actuator deflections to resolutions of 0.1 um in order to verify the mirror behavior.

The baseline payload architecture incorporates a Shack-Hartmann wavefront sensor for mirror characterization. We present a model and analysis of the wavefront sensing capabilities for the 1.5U optical payload. In particular, we look at the achievable wavefront measurement precision given a range of input apertures, detector resolutions, and supporting system optics constrained by the volume requirements of the nanosatellite platform.

9227-4, Session 1

Spectral method for calculating pixel overlap areas applied to multiframe image de-aliasing

Edward Cohen, Richard H. Picard, ARCON Corp. (United States); Peter N. Crabtree, Air Force Research Lab. (United States)

Various techniques have been developed to improve the resolution of sensor-aliased imagery. In the literature these de-aliasing algorithms are sometimes included under the broad umbrella of super-resolution. One basic approach to multiframe de-aliasing is the well-known noniterative algorithm termed variable pixel linear reconstruction (VPLR) or “drizzling.” Many modern techniques are based on iterative optimization of a forward model. Regardless, both iterative and noniterative techniques rely on estimation of frame-to-frame displacements and rotations to subpixel accuracy. Weights are then solved for and used to distribute low-resolution pixel values to a high-resolution grid. One approach used in both VPLR and iterative methods to determine weights is to calculate pixel overlap areas. Well-known spatial domain approaches based on computational geometry exist to perform such calculations. Here we present a novel approach based on calculating overlap areas in the spectral domain, termed the spectral-overlap (SO) method, and include a comparison with the spatial domain approach of O’Rourke. All spatial spectra in the SO method are calculated analytically once and for all, resulting in expressions devoid of quadratures. Initial studies indicate this new algorithm executes roughly 4.6 to 7 times faster as compared to the O’Rourke method; however, excluding time to generate input quantities common to both algorithms, the SO calculations are about 20 times faster. The speedup is partly explained by the ability to precompute many quantities, and apply these quantities to the computation of many distinct spatial overlaps. Application of the algorithm to multiframe de-aliasing is demonstrated using both simulated and laboratory-captured imagery.

9227-5, Session 1

Comparison of sensor noise effects on FITTS and projection based phase only correlation algorithms for high speed video trackers

David C. Dayton, Applied Technology Associates (United States)

The FITTS correlation algorithm has been widely used for over forty years in high speed video trackers. It has the advantage that it is very simply implemented in a digital computer with a small number of calculations. At each step the algorithm attempts to estimate the shift between an image of a moving target and a proto-type image. There are several well-known short comings of the FITTS algorithm. First the error in the shift estimate increases if the shift is greater than one pixel of the digital image. Second the FITTS algorithm is susceptible to errors from sensor noise if the video images have low signal to noise ratio. These errors can force a lower tracker closed loop bandwidth to maintain track loop stability. An alternative correlation tracker algorithm is known as Projection Based Phase Only Correlation. In this paper we compare the two algorithms with respect to the effect of sensor noise.

9227-6, Session 1

Analysis of detection position in wavefront sensor-less adaptive optics systems

Lizhi Dong, Ping Yang, Wenjin Liu, Shuai Wang, Xing He, Bing Xu, Institute of Optics and Electronics (China)

Conventional adaptive optics systems use wavefront sensors to measure the phase aberrations of the incident beams and the control signals are generated accordingly. In recent years, wavefront sensor-less adaptive optics systems have been rapidly developed for their reductions of cost, complexity and availabilities in the cases where wavefront detections are challenging. In wavefront sensor-less adaptive systems, wavefront sensing is often replaced with far-field detection through placing an image sensor or an optical detector at the focal plane of a lens, and some optimization algorithms are introduced to directly optimize the metric of the detected signals. If the detection is not sufficiently accurate, even if the optimal metric is achieved, the correction quality (residual phase aberration or beam quality) may still be poor. Inaccurate far-field detection could be caused by many reasons. In this paper we focus on the effects of improper far-field detection position in wavefront sensor-less adaptive optics systems. At first we build a simple modal of a wavefront sensor-less adaptive with improper detection position. Then a series of analyses are carried out using this modal and the criteria of detection accuracy is concluded. Finally some simulations with different types of deformable mirrors and phase aberration components are presented.

9227-7, Session 2

Statistical bounds and maximum likelihood performance for shot noise limited knife-edge modeled stellar occultation

Patrick J. McNicholl, Peter N. Crabtree, Air Force Research Lab. (United States)

Applications of stellar occultation by solar system objects have a long history for determining universal time, detecting binary stars, and providing estimates of sizes of asteroids and minor planets. More recently, extension of this last application has been proposed as a technique to provide information (if not complete shadow images) about geosynchronous satellites. Diffraction has long been recognized as a source of distortion for such occultation measurements, and models developed to compensate for this degradation. Typically these models employ a knife-edge assumption for the obscuring body. In this preliminary study, we report on the fundamental limitations of knife-edge position estimates due to shot noise in an otherwise idealized measurement. In particular, we address the statistical bounds (both Cramer-Rao and Hammersley-Chapman-Robbins) on the uncertainty in the knife-edge position measurement, as well as the performance of the maximum likelihood estimator. Results are presented as a function of both stellar magnitude and wavelength pass-band of the sensor.

9227-8, Session 2

Effect of different wall thicknesses on the accuracy of through-the-wall radar imaging using biconical antenna array

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Through-the-wall radar imaging (TWRI) is an emerging remote sensing technology to provide see-through-wall ability. There are two outstanding challenges associated with this imaging modality. First, the multiple reflections at the walls can cause a target located closer to it to be obscured. Second, the signal suffers a high transmission loss in the wall as compared in the air. This problem can be modelled as reflection and transmission of electromagnetic wave through a single dielectric slab, whose magnitude depends on the wall permittivity, thickness, incident angle and the wavelength. An experiment was performed to study the effect of different wall thicknesses on the accuracy of a TWRI. A plywood wall model with variable thicknesses from 1 to 4 inches was constructed. A water container measuring 45 x 45 cm and 30 cm height placed 1.5 m above the floor constituted a target. A layer of 12 inches pyramidal absorbers were placed on the floor in vicinity of the wall to mitigate floor reflections. The TWRI consisted of an array of 16 biconical antenna connected to a 2-port vector network analyzer through a 16-port multiplexer. In each procedure, 240 different multistatic transmission coefficients in time domain were measured. The image reconstruction algorithm used is based on beamforming method, integrating the coherence and angle dependant weighting factors. Two metrics were used to quantitatively assess the performance of the system. They are (i) the Target Clutter Ratio (TCR), and (ii) the sharpness. The result indicates both TCR and sharpness are severely affected as the wall thickness increases.

9227-9, Session 2

An iterative procedure for ultra-wideband imagery of space objects from distributed multi-band radar data

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In this work, a novel technique is proposed for ultra-wideband imagery of space objects from distributed multi-band radar data. The complex exponential (CE) model is used for representation of ultra-wideband radar returned signals, where an iterative procedure is developed for optimized model parameter estimation. Based on the optimized CE models for subband signals of distributed multi-band radar data, an ultra-wideband coherent processing technique is proposed, where the de-noising cross-correlation (DNCC) algorithm and statistical method are used to obtain the phase incoherent parameters (ICPs) between subband signals. After compensating the phase ICPs, a coherence function is defined and combined with statistical method to find amplitude ICP. Finally, ultra-wideband data fusion via two-dimensional gapped-data state space approach (2-D GSSA) is applied to multiple subband signals for supper-resolution imagery. Experiments using computational electromagnetic data from the method of moment (MoM) as well as measurement data from an anechoic chamber are conducted to validate the proposed technique, whose usefulness lies in two important aspects: optimized ultra-wideband radar signature modeling and ultra-wideband imagery of space objects from distributed multi-band radar signals.

The paper is to be organized as follows:

1. Introduction
2. Iterative Procedure for Optimized CE Model Representation
3. Multi-band Radar Signal Coherent Processing
4. Ultra-wideband Imaging
5. Experimental Results
6. Conclusions

9227-10, Session 3

A telescopic cinema sound camera for observing high altitude aerospace vehicles

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Rockets and other high altitude aerospace vehicles produce interesting visual and aural phenomena that can be remotely observed from long distances. This paper describes a compact, passive and covert remote sensing system that can produce high resolution sound movies at >100 km viewing distances. The telescopic high resolution camera is capable of resolving and quantifying space launch vehicle dynamics including plume formation, staging events and payload fairing jettison. Flight vehicles produce sounds and vibrations that modulate the local electromagnetic environment. These audio frequency modulations can be remotely sensed by passive optical and radio wave detectors. Acousto-optic sensing methods were primarily used but an experimental radioacoustic sensor using passive micro-Doppler radar techniques was also tested. The synchronized combination of high resolution flight vehicle imagery with the associated vehicle sounds produces a cinema like experience that that is useful in both an aerospace engineering and a Hollywood film production context. Examples of visual, aural and radar observations of the first SpaceX Falcon 9 v1.1 rocket launch are shown and discussed.

9227-13, Session 3

Three-dimensional imaging using differential synthetic aperture interferometry

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Synthetic aperture radar interferometry (InSAR) can gain three-dimensional topography with high spatial resolution and height accuracy using across track interferometry. Conventional InSAR produce three-dimentional images from SAR data. But when the working wavelength transit from microwave to optical wave, the transmission antenna and receive antenna become very sensitive to platform vibration and beam quality. Through differential receive antenna formation, we can relax the requirement of platform and laser using synthetic aperture imaging ladar (SAIL) concept. Line-of-sight motion constraints are reduced by several orders of magnitude. We introduce two distinctive forms of antenna formation according to the position of interferogram. The first architecture can simplify the interferogram processing and phase extraction algorithm under time-division multiplex operation. The second architecture can process the 2D coordinate and height coordinate at the same time. Using optical diffraction theory, a systematic theory of side-looking SAIL is mathematically formulated and the necessary conditions for assuring a correct phase history are established. Based on optical transformation and regulation of wavefront, a side-looking SAIL of two distinctive architectures was invented and the basic principle, systematic theory, design equations and necessary conditions are presented. It is shown that high height accuracy can be reached and the influences from atmospheric turbulence and unmodeled line-of-sight motion can be automatically compensated.

9227-16, Session 3

Experimental resolution comparison between the TOMBO and single lens systems

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Thin Observation Module in Bound Optics (TOMBO) is an optical system that achieves thinness and high-resolution imaging by replacing

a conventional large full aperture by a lens-let array. In the aspect of thinness, the focal length of each lens-let can be 1/n of the conventional single lens system with equal f-number, where n is the number of sub-images of the scene in one direction across the image sensor. The reduction in the focal length of the lens-let (keeping the f-number the same) would keep the focal resolution unaffected with the disadvantage of reduction in angular resolution. In the view of high-resolution, recovering the lost angular resolution by collecting sub-images can be achieved. The lens-let array accumulates a series of sub-images from the same scene which are under-sampled. Each sub-image resolution is determined by pixel size rather than the optical performance of the lens-let, and these sub-images can be processed in a manner similar to multi-frame super-resolution processing to obtain a fully up-sampled, high-resolution image.

While lost angular resolutions can be recovered by collecting sub-images for the TOMBO imaging system, there has been very little work on experimentally evaluating angular resolution performance. Our work focused on the angular resolutions comparison between a 4?4 lens-let TOMBO and Nikon lenses measured by a collimator in the same f number and image sensor condition. Experimental results present the equivalent focal length of the TOMBO.